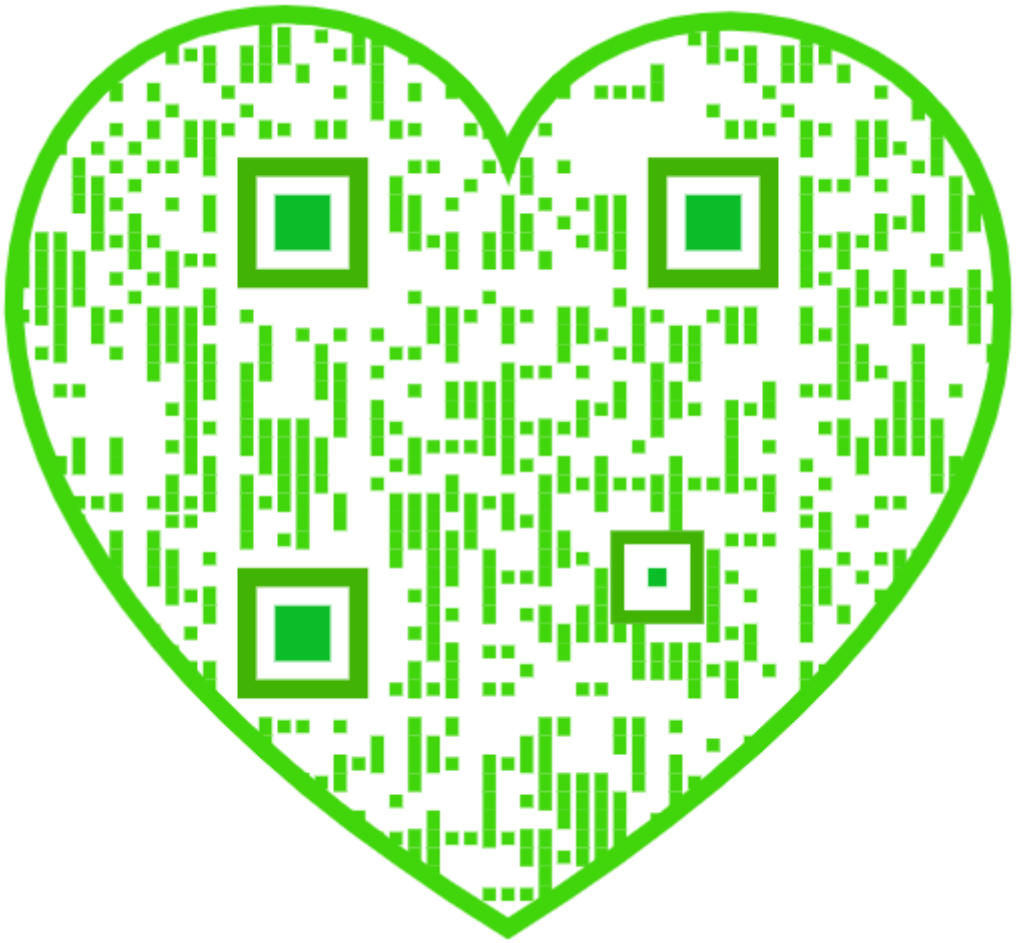

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AIR MINISTRY.

METEOROLOGICAL OFFICE, LONDON.

A SHORT COURSE IN ELEMENTARY METEOROLOGY.

BY

W. H. PICK, B.Sc.

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PREFACE.

This unimposing little book is a remarkable one, for it marks an epoch; there are numerous books on elementary meteorology, but this is the first which has been written by a British teacher for a class of students who are learning meteorology as a qualification for their profession.

The British Empire has produced some of the world's foremost meteorologists—Halley, Beaufort, Abercromby, Blanford, Eliot, and Shaw, to mention only a few—but, until recently, no one but a few specialists thought it worth his while to make a serious study of meteorology. But things have now changed, for the war taught us the importance of meteorology in practical life, and the aviator has arrived with his active life in the region of nature which we meteorologists have only looked into from below.

Meteorology, from being the hobby of a few and the life's work of a still smaller number of despised official "weather prophets," has come into its own, and not only the aviator but the general public is asking for the means to study this neglected branch of science.

It is, therefore, with the greatest pleasure that I welcome this little book and trust that it is only the first of a long series, for meteorology is still in its infancy, and as it develops text-books must be rewritten or they will become worse than useless.

This book has been written by a practical meteorologist for practical aviators and by a teacher for his students. This is an ideal combination and the product is not disappointing. I wish, however, to warn the student that there are many unsolved problems in meteorology, and therefore he should not be satisfied with any explanation or theory which the book contains. He has been given the best explanations which it is possible to give in the present state of our knowledge, limited in some cases by the need to use elementary considerations only. All this should, however, give him a greater interest in his work, for it will afford him plenty of opportunities to use his own brains, to say nothing of the possibility of his making an important discovery. What more could any real student desire?

G. C. SIMPSON,
Director, Meteorological Office.

August 1921.

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A Short Course in Elementary Meteorology.

PART I.—GENERAL METEOROLOGY.

CHAPTER I.

Introductory.

1. *The Atmosphere.*—Man lives at the base of an invisible ocean of air termed the atmosphere. This atmosphere is complex in its chemical composition, but in the lower levels near the earth's surface that composition remains practically constant. Innumerable chemical analyses of samples from these lower levels taken from various regions of the globe have failed to reveal any very appreciable differences. But, partly by reason of different exposure to the sun and partly by reason of the different properties of the land and sea surfaces in contact with it, the atmosphere near the earth's surface, whilst remaining sensibly constant in chemical composition, reveals striking physical differences from time to time and from place to place. These physical differences may be regarded at first sight as comparatively slight, but their results are amazing; for example, 200° F. covers the range of atmospheric temperatures experienced on the earth, and this is almost negligible compared, say, with the difference between the temperature of the electric arc and that of liquid hydrogen, but, nevertheless, small as it is, it causes the great cold of the arctic regions at one end of the range and the sweltering heat of the tropical regions at the other.

The study of atmospheric conditions and changes is called meteorology, and meteorology is a branch of the wider science, physics. The student will find it a great help if he will continually remember this kinship, and will keep always before him the fact that all the conditions and phenomena of the atmosphere are illustrations of the principles of physics, and that the sea of air is a vast physical laboratory in which nature is always showing some experiment or another on the grand scale. It is the function of the meteorologist to note the conditions of these experiments and to make an attempt to explain the results which become evident during the course of them.

2. *The Value of Meteorology.*—It requires no great amount of reflection to realise that the weather is an important matter to most men, no matter what their occupation may be. It is ever present, whether in peace or war, and must be taken into account in most projects. The mariner and the agriculturist find it of supreme importance. The housing engineer, engaged

in erecting buildings in any particular country, must have a knowledge of the climatic extremes likely to be experienced in that country. Medical men realise that there is a distinct relation between the weather and the prevalence of certain diseases. The commander-in-chief conducting military operations is brought face to face with the fact that favourable or unfavourable weather is a factor too great to be disregarded; whilst the gunnery officers have to institute a close liaison with the meteorological ones if they are to secure accuracy of range. And, apart from specialists such as those of the classes already mentioned, even the average citizen dwelling in town or country is often enough made to realise by unfortunate experience of snow or fog or floods how dependent upon the weather is the transport which brings to him the supplies of the necessaries of life.

3. *The Value of Meteorology to the Airman.*—The coming of aviation has added yet more strongly to the importance of a study of meteorology for, to the airman, a knowledge of it is of peculiar importance inasmuch as the air is the medium in the which he has his flying being and is the medium, the changes and phenomena of which may cause him considerable perturbation from time to time. A well-founded forecast of coming weather changes—and prediction is part of the work of meteorology—is to him a necessity enabling him, first, to avoid the danger which may come to him as a result of those changes; and second, to put himself in a position to be able to utilise those changes to his own advantage if this be possible. But it cannot be too much emphasised that these changes, important, and even deadly as they may be to him, cannot be foretold by even an expert meteorologist by just a casual glance at the sky and a casual tapping of the "weather glass," but that their prediction requires a wide-flung organisation, daily weather charts, much careful observation and study, and continual appeals both to precedent and to physics.

It must not be supposed, however, that prediction is the only help that meteorology can give to the airman. Forecasting is a matter of the vicissitudes of the weather, but for such matters as the floating of an airship or the working of a petrol engine a knowledge of the normal atmospheric conditions at various heights is of more importance than that of the temporary divergencies with which forecasting is concerned. Climatic data, that is data dealing with means, either monthly or yearly, of the various meteorological elements is just as important in its own way and for its own uses as is the forecast of to-morrow's weather. Prediction is so attractive a part of the science of meteorology that there is often a tendency to consider it the only part.

CHAPTER II.

Winds.

4. *General.*— Wind can neither be measured like temperature nor can it be seen and painted like clouds. For these reasons man has always been ready to believe that there is something vague and illusory about it, that it "bloweth where it listeth," and that any attempts to study it are foredoomed to failure. Going back a little more than a century, it is probably true to say that less was known about wind than about any other common meteorological element. Its direction could be estimated at any moment, but its force was only able to be very vaguely indicated by the loose nomenclature of airs, breezes, catspaws, squalls, gusts, and the like.

5. *The Beaufort Scale.*—In order to lend precision to personal estimation of wind force, Admiral Sir Francis Beaufort, then Hydrographer to the Navy, devised in the year 1805 a scale of numbers ranging from 0 to 12, based upon the amount of sail that a well-conditioned man-of-war could carry in winds of various forces. The figure 0 corresponded with a calm and 12 with a hurricane "that no canvas could withstand." Sailing ships gave way to ships driven by steam, but still the tradition was carried on until by the end of the century it was realised that a restatement of its specifications was long overdue. The revised scale is given in Table I. It will be seen that separate criteria are given to the observer on coasts or inland. In the inland scale, drawn up by Dr. G. C. Simpson, F.R.S., in 1905, it will be seen that the observer is advised to take into account such points as the movements of twigs and branches and various degrees of structural damage. In the coast scale, also due to Simpson, attention is directed to the behaviour and rigging of smacks. Comparison of the estimates given by experienced sailors with the velocities recorded by instrumental measurements has enabled limits of velocity to be assigned to the various numbers of the scale.

The scale may seem somewhat crude, but in practice it is found to give good results. Its use is enhanced by the fact that at many meteorological stations no special apparatus for measuring wind is installed. For the use of observers at such stations, and for the individual making a survey of weather conditions away from a station, a scale such as the Beaufort is a necessity.

TABLE I.

The Beaufort Scale of Wind Force with Specifications and Equivalents.

Beaufort Number.	General Description of Wind.	Specification of Beaufort Scale.		Limits of Velocity in Miles per Hour at about 30 feet above level ground.
		For Coast use.*	For use Inland.	
0	Calm	Calm - - - - -	Smoke rises vertically -	Less than 1
1	Light air	Fishing smack just has steerage way.	Wind direction shown by smoke drift but not by wind vanes.	1-3
2	Slight breeze.	Wind fills the sails of smacks, which then move at about 1-2 miles per hour.	Wind felt on face; leaves rustle; ordinary vane moved by wind.	4-7
3	Gentle breeze.	Smacks begin to careen and travel about 3-4 miles per hour.	Leaves and small twigs in constant motion; wind extends light flag.	8-12
4	Moderate breeze.	Good working breeze; smacks carry all canvas with good list.	Raises dust and loose paper; small branches are moved.	13-18
5	Fresh breeze.	Smacks shorten sail - -	Small trees in leaf begin to sway.	19-24
6	Strong breeze.	Smacks have double reef in main sail.	Large branches in motion; whistling in telegraph wires.	25-31
7	High wind	Smacks at sea lie to -	Whole trees in motion -	32-38
8	Gale	All smacks make for harbour.	Breaks twigs off trees; generally impedes progress.	39-46
9	Strong gale	- - - - - -	Slight structural damage occurs; chimney pots removed.	47-54
10	Whole gale	- - - - - -	Trees uprooted; considerable structural damage.	55-63
11	Storm	- - - - - -	Very rarely experienced; widespread damage.	64-75
12	Hurricane	- - - - - -	- - - - - -	Above 75

* The fishing smack in this column may be taken as representing a trawler of average type and trim.

6. *The Pressure Tube Anemometer.* — An instrument for writing a continuous record of the wind from moment to moment with regard to its changes of velocity has been devised by W. H. Dines, F.R.S., and is generally known as the "tube anemometer." Instrumental measurements of wind have obviously very definite advantages over the cruder method of personal estimation.

The pressure tube anemometer consists of two parts—the head and the recording apparatus.

The construction of the head will be understood by reference to Fig. 1. It is mounted on the top of a long pole which is 40 or 50 feet above the ground level and sometimes even more. The upper part of the head is free to rotate, and this

ensures that the open end of the horizontal tube *A* is kept facing the wind by the vane *V*, which is attached to the opposite end of the tube *A*. The wind, blowing directly into the open end, produces an excess of pressure there which is transmitted through the central tube of the head down to the recording apparatus below by means of flexible tubing attached to the arm *B*. The fixed part of the central tube is surrounded by another tube *S*, which is pierced by four rings of small holes. The wind blowing past these holes produces a diminution of pressure within the space between the two tubes, and this diminution of pressure is transmitted also to the recording apparatus by means of a separate length of flexible tubing attached to the arm *C*.

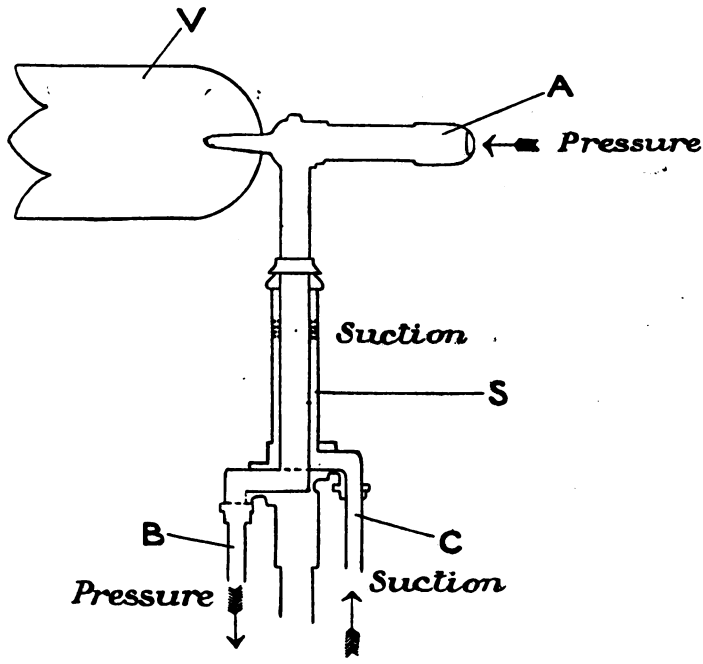

FIG. 1.—Head of Dines Pressure Tube Anemometer.

The recording apparatus is seen in Fig. 2. A vessel *F*, with a peculiarly shaped inner surface *E*, floats inverted in a closed tank *T* partially filled with water. The pressure tube, that is the tube directly attached to the open end of the horizontal tube *A* (*see* Fig. 1) and in which there is an excess of pressure, opens above the water level inside the inverted floating vessel F, and thus the increase of pressure is directly directed against the base of that inverted float tending to cause it to rise. This pressure tube is marked *P* in Fig. 2. The other tube, which may be termed the suction tube and which transmits the decrease of pressure caused by the wind blowing

past the four rings of small holes in the outer tube of the head, communicates with the space above the float. This suction tube is marked *S* in Fig. 2. When any wind is blowing there is an increase of pressure caused within the float and a decrease of pressure caused above the float. The float, therefore, rises, the rise being greater the greater the velocity of the wind. A record of the motion of the float is thus a record of the wind blowing past the head.

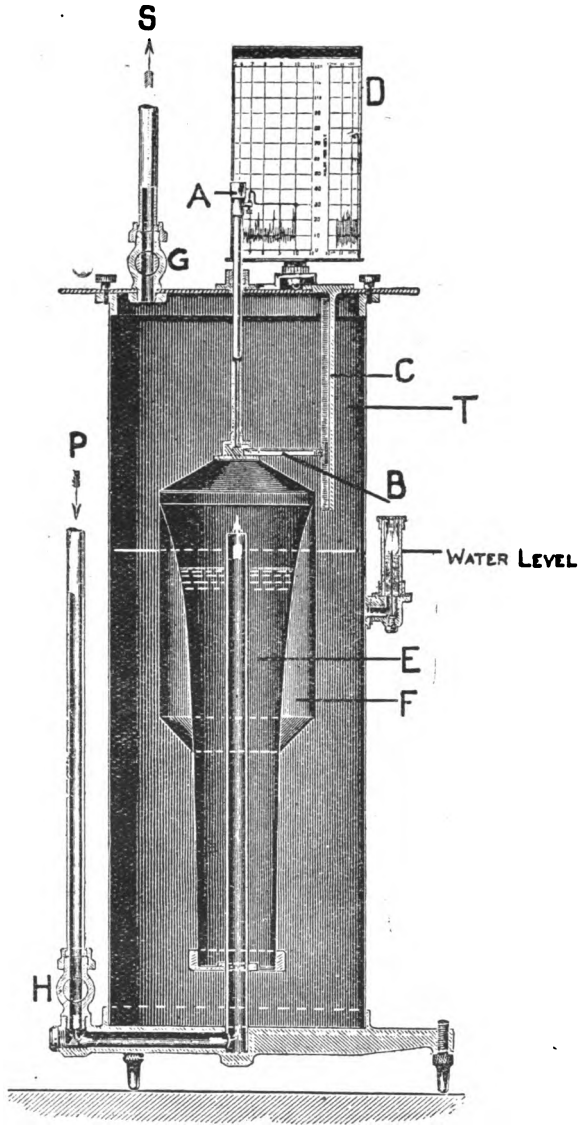

FIG. 2.—Recording Apparatus of Dines Pressure Tube Anemometer.

To face page 11.

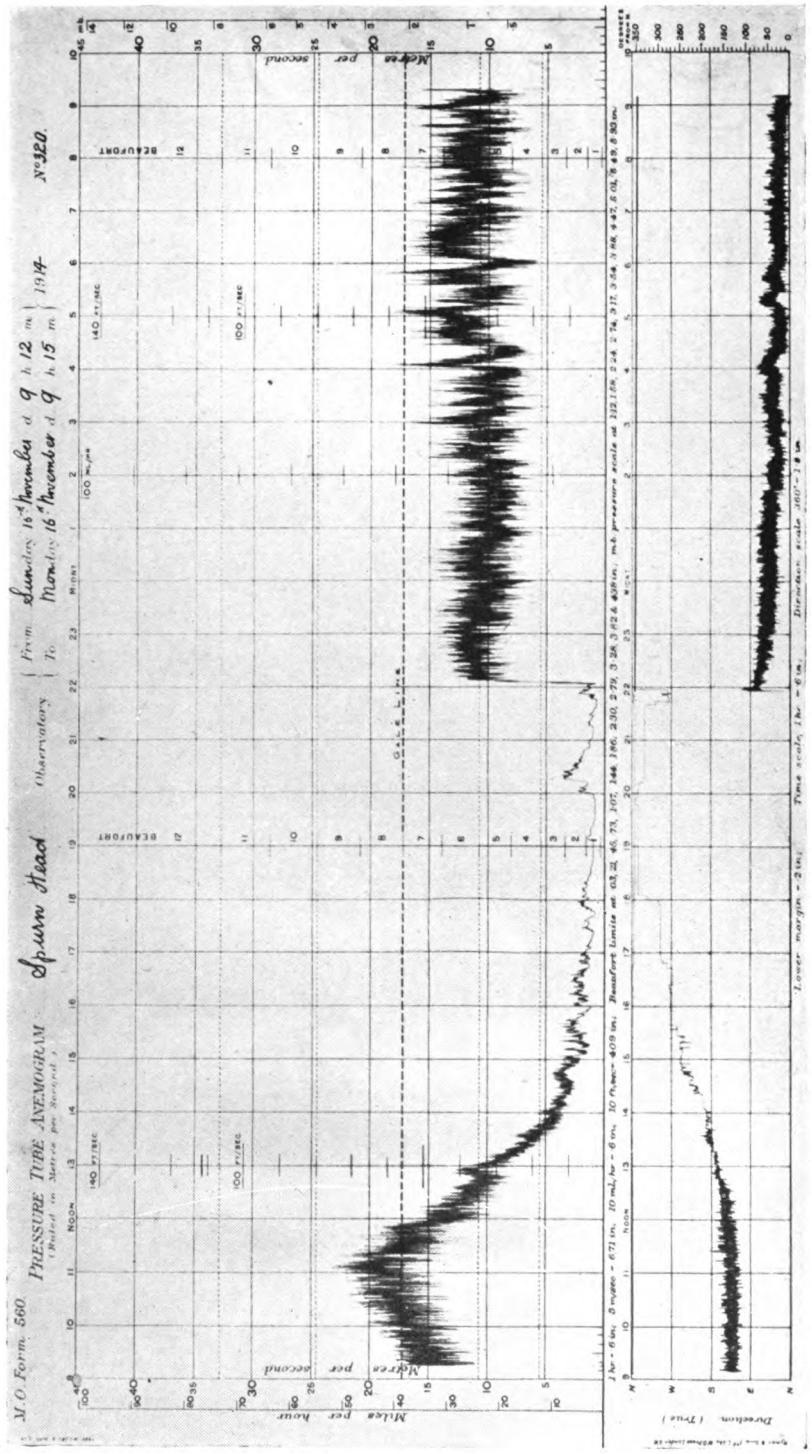

FIG. 3.—ANEMOGRAM FROM SPURN HEAD, 15TH AND 16TH NOVEMBER, 1914.
Showing wind velocity by the pressure tube recorder and wind direction.
Note the difference of timing between the velocity pen and the direction pen.

The arrangement for tracing this record is also shown in Fig. 2. A vertical rod *A* is attached to the top of the float. The rod passes through an airtight cover in the top of the tank *T* and carries a pen which marks on a drum *D* which is kept rotating by clockwork. The float is kept from rotating by the device of a guide *B* attached to it, this guide working in a vertical slot *C*.

G and *H* in Fig. 2 represent stopcocks which, when opened, allow the spaces above and below the float to be placed in communication with the air of the room. This means that the pressures on either side of the float are made the same and thus the stopcocks are of great value for adjustment purposes.

The instrument as described gives only a continuous record of the velocity of the wind; but modifications of it have been devised to enable it to give a continuous record of the direction as well.

7. *The Structure of the Wind.*—An example of a "trace" given by such a combined direction and velocity anemometer is shown in Fig. 3. This particular record was taken at Spurn Head; but the lessons to be derived from it are quite general. Those lessons relate to the structure of wind. Anemometer traces are the best means available of showing what wind really is like. It is never a perfectly steady "blow," but is a perpetual succession of "gusts" and "lulls" with continual slight variations in direction. The width of the ribbon representing the velocity falls off as the velocity gets less. In other words the range of the gusts diminishes with diminishing velocity. It would seem, therefore, that gustiness represents the eddies set up by mechanical obstacles. This view is supported by the fact that if the anemometer be set up over tree tops the gustiness is found to be largely increased, whilst over the open sea it is considerably diminished. But it is equally true that gustiness is never entirely eliminated, being found even in the exposures most free from mechanical obstacles and also at heights of several thousands of feet.

8. *Squalls.*—The wind, however, is not only liable to these small but continually recurring variations known as gusts, but also to more considerable fluctuations of velocity known as squalls. Gusts must be distinctly distinguished from squalls. A squall is a blast of wind, of higher velocity than has been experienced on the average, occurring suddenly and lasting for some minutes at least and then dying away as suddenly as it arose. A gust is also a sudden increase of wind, but it is of very short duration. Squalls are probably due to definite meteorological causes, though this cannot be stated with certainty; gusts are due to the mechanical interference of obstacles in the way of the wind.

9. *The Exposure of a Wind Station.*—From what has been already said, it will be realised that the exposure of a wind

station is of the greatest importance. Just as running water forms eddies and ripples around every obstacle in its path, so will wind which is only running air; and these wind eddies once formed seem to possess the power of persisting for a while with an independent existence of their own. Wind eddies, then, must be formed at the corners of every house, over every little hillock, on the faces of cliffs, around every tree or shrub, or in the immediate neighbourhood of anything rising above the level of the ground. A wind measurement made in close proximity to any such obstacles cannot be a true measure of the general flow of the air; and for general meteorological purposes it is this general flow which is required. An observer, taking a wind observation, should be diligent in taking it in the most open exposure possible. The vitiating power of buildings, trees, and the like cannot be over-estimated. A wind vane, for example, placed just above the roof of a house is thoroughly bad; this exposure is especially commented upon as it is so common.

CHAPTER III.

The Trade Winds.

10. *The Trade Winds.*—Winds may either form part of great atmospheric movements, of a scheme of planetary circulation, or they may be local in character. Of the former class the trade winds are the outstanding example; of the latter those accompanying cyclones and anti-cyclones (which winds will be treated later), or land and sea breezes are illustrations.

Just as water will flow from places of higher level to those of lower, and as electricity will flow from points of higher potential to those of lower, so air will flow from places of higher barometric pressure to places of lower.

This consideration is of great importance when the general arrangement of barometric pressure over the earth is taken into account. The general arrangement is as follows. Two belts of air at high pressure encircle the earth, the belts being enclosed approximately between the lines of latitude 30° N. and 40° N., and between the lines 30° S. and 40° S., whilst a belt of lower pressure lies along the equator, and great areas of low pressure surround both of the geographical poles. Remembering, then, that a wind's direction is that *from* which it blows, and also that air flows from places of higher pressure to places of lower, it would appear that, if no other factor operated, there should be northerly winds blowing from 30° N. latitude towards the equator, and southerly winds blowing from 30° S. latitude also towards the equator. Similarly, southerly winds should blow from 40° N. latitude towards the North Pole, and northerly winds from

40° S. latitude towards the South Pole. These expected winds are shown in Fig. 4, which also shows the general distribution of pressure over the earth. The figure is shown in plan; the winds would actually, in the conditions assumed, blow along meridians.

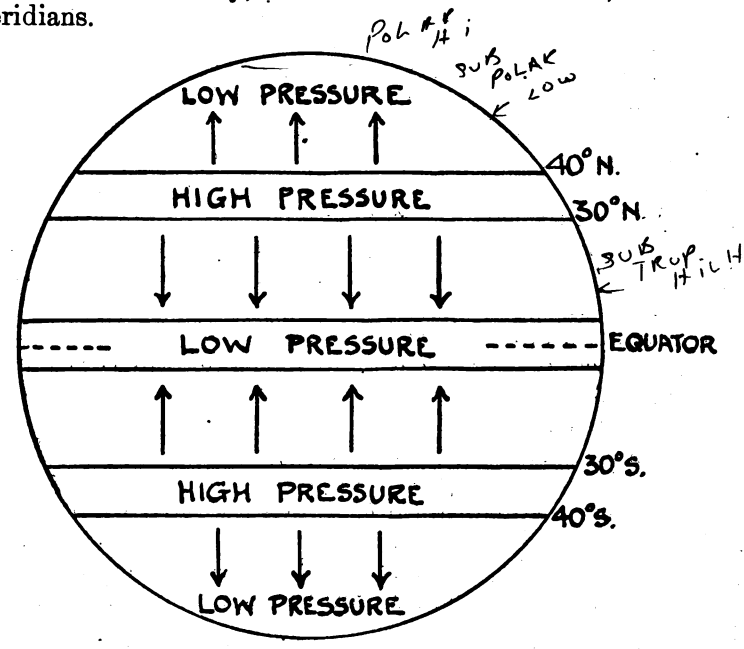

FIG. 4.—General Scheme of Pressure over the Earth with Winds as they would be if the Earth did not rotate.

But a most important other factor does operate. The earth rotates about its axis once in every 24 hours approximately. The speed of rotation of any point on the equator is about 1,000 miles per hour, and this speed falls off with increasing latitude until at either pole it is zero.

Foucault, the great French physicist, showed that a large pendulum, hung suspended in such a way that it could move in any plane, once set swinging apparently changed the plane of its swing slowly but regularly. If the pendulum were started swinging from north to south, it was found after a certain time to be swinging from north-east to south-west, and after a further time from east to west, and so on around in a clockwise direction. The student is referred to any good text-book of physics for the actual details of this fundamental experiment. The great point to be realised is that any pendulum so hung freely suspended does not really change its direction of swing in space; it remains in a state of uniform motion in a uniform direction, and the apparent twisting of its plane of swing is due to the rotation of the earth.

An analogy may be drawn from a passenger on board a ship. If the ship be at rest the passenger has no difficulty in walking

parallel to the planking of the deck. If, however, the ship be suddenly swung rapidly round to the right the passengers finds it an exceedingly difficult matter to maintain his walk parallel to that planking, but tends to deviate to the left. If the ship be swung rapidly towards the left his tendency is to deviate to the right. What really happens is that the passenger tends to maintain his direction of motion unchanged with regard to objects outside the ship, but that the rotation of the ship gives him an apparent motion to the left or right as the case may be.

Every moving body on the earth, whether it be a bullet fired from a rifle, a steamship travelling over the seas, or a particle of air moving to form wind, is subject to the same truth, for the earth is continually rotating. The moving body keeps on in its original direction ; the rotation of the earth causes it to have an apparent deviation.

The general law has been stated thus. Every body moving on the surface of the earth is deflected to the right in the northern hemisphere, and to the left in the southern hemisphere because of the earth's rotation.

Let particles of air be imagined just above the surface in 30° N. latitude. They are impelled by the difference of pressure to move equatorward to form a northerly wind, but the law just enunciated shows that they will be deflected towards the right as they are in the northern hemisphere, and hence the northerly wind will become a north-easterly one, the north-east "trade."

A similar application of the law of deviation will reveal how the southerly wind blowing from 30° S. latitude becomes converted into a south-easterly one, forming the south-east "trade." Care must be taken to apply that part of the law which has reference to the southern hemisphere.

It will be noticed, too, that the winds blowing from the south from 40° N. latitude towards the North Pole, and the northerly ones blowing from 40° S. latitude towards the South Pole become westerly or south-westerly in each case by similar applications of the law.

The scheme of the winds as they actually blow is shown in Fig. 5. This figure is complementary to Fig. 4 and should be studied in conjunction with it.

It is interesting to notice that the name "trade" was not given to these winds because of their benefit to commerce, great as this was in the days of sailing ships, but because they are "track" winds, winds keeping to one track. The north-east and south-east trades blow at sea with remarkable steadiness. This uniformity must not, however, be exaggerated. Sometimes they weaken or shift and their direction is apt to be subject to considerable variation when they encounter islands. This latter variation is most marked about the larger island groups of the Pacific Ocean, especially the Fiji and Samoa ones. Occasionally, too, they are invaded by revolving storms which

control the winds temporarily; and near coasts they are interrupted by the phenomena of land and sea breezes.

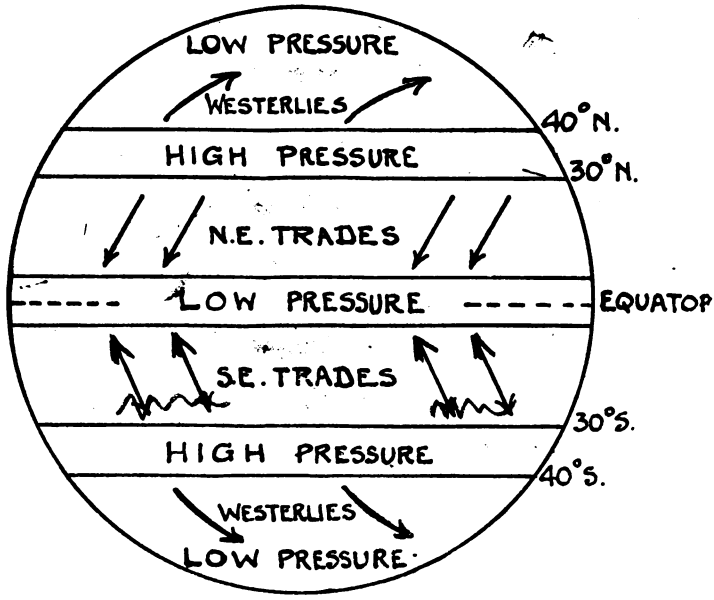

FIG. 5.—Scheme of Winds as they actually blow taking into account the Rotation of the Earth.

The great streams of air constituting the trade winds average nearly 2 miles in depth. The north-east trade over the Atlantic has a mean velocity for the whole year at the surface of about 10·5 miles per hour, varying from a mean of about 7·5 miles per hour in October to a mean of about 13·5 miles per hour in April. The south-east trade over the Atlantic has a higher mean velocity of about 14 miles per hour for the whole year, varying from a mean of about 13 miles per hour in January to a mean of about 15 miles per hour in April, June, and August.

11. *The Doldrums.*—The Doldrums lie between the steady trades and in the immediate neighbourhood of the equator. The Doldrum belt is a region of light and variable winds with many calms and is characterised by cloudy skies, sultry weather, much rain and exceptionally violent thunderstorms. In the days of sailing ships this region was much dreaded by mariners who were liable to lie becalmed there for considerable periods with dire results in regard to their temper and health. The reason for the name is sufficiently clear.

12. *The "Roaring Forties."*—This name is given by sailors to the region between 40° S. and 50° S. latitude. Here there is a more uninterrupted surface of ocean than is to be found in

any other region, and the westerly winds blow from the outer margin of the south-east trade belt with great regularity and with greater strength than do the trade winds. The constancy of these winds, the "brave west winds," is so great that even now sailing ships are enabled to compete by their aid with steam ships in trade with New Zealand via the Cape of Good Hope, the return journey being made around Cape Horn.

13. *The Westerly Winds of the Northern Hemisphere.*—The westerly winds blowing from the outer margin of the north-east trade belt are by no means so steady as are the "brave west winds" of the southern hemisphere. They are very frequently interrupted by storms, and, indeed, the northern temperate zone on land is characterised by such a succession of shifting winds that the prevailing direction of wind movement from the south-west or west is not very apparent until careful records are made and examined.

CHAPTER IV.

Monsoons and Similar Winds.

14. *The Unequal Heating of Land and Water.*—The sun, whilst above the horizon, is pouring down a continuous stream of radiant energy, or, as it is alternatively termed, "insolation." It cannot be too clearly realised, however, that whilst on its way from the sun to the earth, this insolation is not heat. It was excited by the heat of the sun and it produces heat when its energy is absorbed by any material particles on which it may fall; it must be regarded as only a particular form of energy until it is so absorbed, a form of energy having a definite velocity of propagation which is equal to that of light. Even at the cost of repetition it is again stated that only when this radiant energy is absorbed by material particles does it manifest itself as heat, and consequently as a rise in temperature. But the nature of the material on which the radiant energy falls is of great importance in determining how much absorption shall take place and consequently how much rise of temperature shall ensue. Every different substance has to absorb a different amount of heat to produce the same rise in temperature.

The different behaviour of land and water surfaces subjected to the same amount of insolation from the sun has far-reaching effects in nature. Only the surface of the land is heated and it is practically the same surface all the time. In the case of water this is transparent to some of the radiant energy, which therefore passes through to be absorbed by the lower layers. The heat in the case of water is thus more widely distributed

than in the case of land and consequently the rise of temperature in the water surface is proportionately diminished. But there is a more important factor than this: the specific heat of land, that is the heat required to raise a unit mass of it through a unit rise in temperature, is much less than that of water. There is the further point, too, that some of the insolation absorbed by the water is used in bringing about evaporation and insolation so used is not available to bring about any rise in temperature.

A consideration of the three factors mentioned will reveal the very important result that the surface of land is warmed to a considerably higher temperature than the surface of water when the two surfaces are exposed to equal amounts of insolation.

But when the sun, the source of the radiant energy, goes below the horizon, the earth begins to pay back to space the energy it has received. If there is income of energy there is also expenditure of energy; absorption is countered by radiation; and it is one of the most important laws in the science of heat that a good absorber is also a good radiator. The result of this is that as a land surface is a better absorber than a water surface, so also it is a better radiator than a water surface. The total effect of this is that a land surface gets heated quicker and rises to a higher temperature than a sea surface during the hours that the sun is above the horizon, but loses its heat quicker and falls to a lower temperature than does the sea surface during the hours of night. In the last sentence it must be understood that the land and sea surfaces are subjected to the same amount of insolation.

Clouds prevent the full effects of both absorption and radiation of radiant energy so far as the surface of the earth (including both land and water) is concerned. During the day time, if the sky be cloudy, the insolation from the sun has to pass through the clouds before it can reach the earth. It does not accomplish this passage without loss, for the clouds are composed of material particles, and it is a property of such particles that they absorb some of the radiant energy falling on them. Some of the energy, too, is reflected from the top surfaces of the clouds. Consequently, on a cloudy day, less radiant energy actually reaches the surface of the earth than on a day of clear sky; hence there is less heating of both the land and water of the earth. At night, too, clouds radiate heat and also reflect some of the radiation emitted by the earth's surface back to that surface, so that on a cloudy night the land and water surfaces do not cool so much as on a clear sky night. For the maximum effects of both absorption and radiation to be made manifest a clear sky is necessary. Fog or mist acts in a similar way to cloud; this would be expected, as fog or mist is only cloud at the surface of the earth.

15. *Land and Sea Breezes.*—The foregoing considerations are of great importance in explaining land and sea breezes. As the day progresses the land gets rapidly warmer than the sea. Consequently, in its turn, the air over the land becomes heated more than does the air over the sea. The warmer air then sets up upward convection currents on account of its lessened density and a cooler breeze flows in from the sea to take the place of the air which has risen. During the night the reverse process takes place. The sea, through losing its heat by radiation at a much less rapid rate than does the land, becomes warmer than the land. The upward convection currents now occur over the sea and a breeze off the land sets in.

It is clear that the land and sea breezes introduce a levelling effect upon the temperatures experienced in coastal regions. They prevent great extremes as, compared with temperatures inland in the same latitude, the land temperature is made lower by day and warmer by night.

In such a region as the British Isles the phenomena of land and sea breezes are often masked by cyclonic disturbances (*see* Part II.), but in tropical regions they are much more important. In those regions the diurnal temperature variation is very marked, and cyclonic storms are by no means so frequent. In some tropical places where the configuration of the land favours their development, the land and sea breezes attain to great strength. This is particularly the case at Port Royal, in Jamaica.

Normally, in nearly all latitudes, the land breeze sets in at about 8 o'clock in the evening and reaches its maximum strength at about 3 o'clock in the morning. Conversely, the sea breeze sets in at about 9 or 10 o'clock in the morning, attaining its maximum strength at about 3 o'clock in the afternoon.

Some doubt exists as to the depth to which the land and sea breezes extend landwards or seawards as the case may be. Along the coasts of the United Kingdom the sea breezes probably extend about 10 miles inland, whilst the land breezes reach a slightly less distance seawards. In tropical regions these extensions are greater.

16. *Monsoons.*—Well marked differences of temperature between land and sea surfaces may arise either as a result of rapid diurnal heating and cooling, which is the cause of the land and sea breezes, or as a result of rapid seasonal heating and cooling. Over the centre of large continents far removed from the sea the seasonal variation of temperature is greatest; summer being characterised by a very high mean temperature and winter by a very low one comparatively. As a result, the pressure over the land in summer is much reduced, becoming less than that over the surrounding less warmed seas, whilst in winter the reverse is the case. Consequently winds blow

outwards from the land towards the seas in winter, and inwards from the seas to the land in summer.

These winds changing with the seasons of summer and winter are the monsoons.

The monsoons of India are the best known winds of their class. The hot weather in India usually commences about February and continues on until June. The heating process goes on for a considerable period before the actual reversal of wind direction takes place. When the reversal does occur, it comes suddenly and is generally accompanied by stormy weather. The wind then begins its "blow" from the south-west, mainly directed towards the high lands of the Himalayas with an appreciable turn to the right in accordance with the law of deviation due to the rotation of the earth, which has already been enunciated. The south-west monsoon blows up to about September or October and the whole season is one of rain. The winds of the summer monsoon attain to great strength.

In winter, the summer monsoon from the south-west is replaced by one from the north-east flowing out from the main land masses towards the sea. This monsoon, flowing from such a huge area of land, is a dry wind, rain only occurring lightly and irregularly. The wind force in this monsoon is considerably less than that in the south-west one.

For most continents the monsoon effect is comparatively insignificant. Asia, especially in India and China, shows it most distinctly, and there, in fact, it is the predominating feature of the climate. Australia, too, shows it in some degree, but the reversals are hardly abrupt enough to justify the use of the special term in its usual connotation. The equatorial regions of Africa show it to some slight extent; but it hardly appears at all on the American continent. So far as Europe is concerned there seems to be a slight monsoonal effect observable on the Iberian Peninsula and that is all.

17. *Katabatic and Anabatic Winds.*—Claiming some sort of kinship with land and sea breezes and with monsoons are what are termed katabatic and anabatic winds.

At night there is greater radiation from high ground than from valleys, greater radiation because at higher altitudes there are less dust particles or water vapour particles in the air to intercept the radiation and thus to absorb or reflect it. The colder land means colder air in contact with it. Colder air is denser air, which, therefore, by gravitational action slides down the slopes. These winds caused by the gravitation of cold air off high ground are katabatic winds. Such winds are local but are very frequently observed, especially at night.

An example on the large scale is found in the Northern Adriatic in the cold and very violent wind which sometimes blows down the slopes of the plateau to the north and is termed the "Bora." The plateau becomes very cold in the clear

weather which often occurs in winter, much colder than the valleys below it, and, consequently, a stormy descending current of air is started which persists, when conditions are favourable, for considerable periods.

The converse of katabatic winds is seen in the daytime. Then, the land in valleys becomes warmed which warms the air in contact with it, and this causes convection currents to rise up the slopes of the surrounding high lands. Such up currents constitute anabatic winds. They do not approach the violence which characterises some examples of katabatic winds.

Note.—It should be noticed that all the winds treated up to the present are quite distinct from those non-periodic winds due to travelling cyclones and anti-cyclones. A consideration of the winds accompanying those systems is deferred until those systems themselves are treated.

18. *The Lull of Wind at Night.*—An extended investigation of wind records kept at any land station will reveal the noteworthy fact that, generally, the wind drops in force after sunset and remains lulled until after sunrise. This must not be taken as true for every night, for travelling cyclonic systems quite often cause this, the normal lulling, to be entirely masked. Eliminating these travelling systems, however, the statement remains true. The nightly lull is not so marked far out at sea nor is it at even the modest height of the Eiffel Tower in Paris.

The cause of the lulling appears to be found in the following considerations:—

In day time, especially in the summer, the surface layers of air get considerably warmed through contact with the rapidly absorbing and hence rapidly warming surface of the land. The warmed surface air then rises to mingle with the currents a little higher up. The upper air currents have more energy because they are not subjected to the friction of the earth's surface. It will be recognised, then, that the rising of some of the less energetic surface air will tend to slow down the currents just above the surface layers while the coming down of some of the more energetic air of these upper layers (coming down because colder and thus denser) to take the place of the risen air will tend to increase the velocity of the currents in the surface layers.

At night, no air rises and hence the velocity of the currents just above the surface layers tends to increase upon what it was during the day, as it is no longer subjected to any "brake" effect, whilst no more energetic upper air comes down to increase the velocity of the surface currents.

Under normal conditions, then, the wind at the surface lulls at night whilst the wind just above the surface layers, say, up to 1,000 feet, tends to freshen. During the day, the reverse happens; the wind in the surface layers tends to increase in velocity and the wind up to 1,000 feet to decrease.

As would be expected from what has gone before, the surface lulling of wind is more marked during a night of clear sky than during one which is cloudy or overcast, for it is on such clear nights that the radiation from the earth is greatest and hence that cooling is greatest; and the greater the cooling of the earth's surface the greater will be the cooling, and thus the density, of the air in contact with that surface; and such a greater density means a greater lulling of the wind.

CHAPTER V.

Some Considerations on Temperature.

19. *Heating due to Compression.*—The absorption of insolation is not the only means by which temperature may be raised. There is the heating due to mechanical compression. Tyndall showed this effect by his device of a glass syringe in which a piece of tinder or some other combustible substance was placed. By pushing in smartly the piston of the syringe, the combustible substance could be set alight. The same phenomenon is within the experience of any one who has pumped up the tyres of a bicycle. The pump soon becomes warm. In each case the compression of air has produced heat. In each case, too, the conditions are such that practically no heat can be transferred to, or taken from, the air compressed, either by conduction or radiation. Such conditions are said to be "adiabatic" and the heating produced is purely dynamical.

20. *Cooling due to Expansion.*—The effect considered above is entirely reciprocal. If compression causes heating, expansion causes cooling. The expanding gases have to do work in pushing away the surrounding air. To do this work they must derive energy from themselves if the conditions are assumed to be approximately adiabatic. This energy must come from the store contained in the vibration of the molecules of which the gases are composed. Consequently, the molecules vibrate a little less quickly and this, following the kinetic theory of gases, means a fall in temperature.

21. *Adiabatic Changes in the Atmosphere.*—As has already been stated, the essential matter in an adiabatic change is that no heat must either get to, or be taken from, the substance under investigation. Such a condition of things is realised in the atmosphere in the interior either of ascending or descending masses of air. Ascent or descent means entry into regions either of less or greater pressure with consequent expansion or compression and resulting dynamical cooling or heating. Such dynamical changes are of the greatest importance in meteorology as

they are vital, as will be seen later, in explaining the formation of clouds and rain.

22. *The Vertical Temperature Gradient.*—In ordinary still air, that is, air without vertical components of motion, the temperature falls off generally at the rate of approximately 1° F. for every 300 feet of ascent.

The rate of fall of temperature of ascending air due to dynamical cooling is also fairly accurately known. It is about 1° F. for every 185 feet of ascent. This is termed the adiabatic gradient.

Considering air rising, then, the ascending air falls in temperature at the rate of 1·6° F. in 300 feet, whilst the surrounding air only falls at the rate of 1° F. in the same range. Thus the rising air is falling in temperature at the rate of 0·6° F. for every 300 feet compared with the surrounding air. But the rising air probably started to rise owing to the fact that, in the first place, it was slightly higher in temperature, through some cause or another, than the air which surrounded it near the ground. As it is falling in temperature compared with its surroundings during the ascent at the rate of 0·6° F. for every 300 feet it will be seen that it will soon arrive at such a height that its temperature will become equal to the temperature of its surroundings. When this point is reached, no further ascent will occur.

23. *Temperature Inversions.*—It has been said that temperature decreases in still air with ascent above ground level. Though this is generally the case, it is not invariably so. Sometimes the air increases in temperature as one ascends. Such a condition is known as an inversion of temperature. Such inversions are common during clear sky nights in winter when radiation from the earth is able to act longest and to exert its maximum effect in lowering the temperature of the surface. The great cooling of the surface chills the air in contact with it to such an extent that its temperature falls considerably below that prevailing in the atmosphere 200 or 300 feet up.

Nor do inversions invariably occur in the neighbourhood of the surface. Quite often they are encountered in isolated layers in the upper air well above the surface. Inversions occurring thus generally mark the margins of cloud layers.

24. *Distribution of Temperature over the Globe.*—Little need be said under this heading as any good book on Physical Geography will give the details required. The maps used to demonstrate the distribution are constructed by the use of isotherms, that is, lines drawn through places having the same temperature. Isotherms on such maps refer to temperatures at sea level, and hence in order to find from them the actual temperature at a given place, the height of the place must be

noted and an allowance of 1° F. decrease per 300 feet of elevation must be made. It should be recognised, too, that the temperatures plotted are mean temperatures over, generally speaking, a considerable number of years.

The isothermal charts for July and January are especially worthy of study. In the July chart the maxima in the centres of the great land masses like North West India and the Sahara should be noticed. Those maxima would be expected to occur where they do because the sun is nearly overhead there and thus is pouring out a great stream of insolation which the land surfaces greedily absorb with a resulting great rise in temperature. The comparatively low temperatures of the oceans in the same latitudes as the land masses in question are also noteworthy as illustrating the different degrees of heating of land and water when subjected to the same amount of insolation. The bending of the isotherms as they strike the coasts is also interesting in the same connection.

In the January chart the maxima occur in the land masses of the southern hemisphere as would be expected as a result of the migration of the sun across the equator towards them. The minima in the land masses of the northern hemisphere, for example, in Asiatic Siberia, should also be noticed. These northern districts receive little insolation during their winter and, hence, the good radiating power of land comes fully into play with a consequent great fall in temperature.

25. *Annual Range of Temperature.*—Facts concerning the annual range of temperature in various places may also be learned from a consideration of isothermal charts of the globe. The area of moderate annual range, that is, of less than 10° F. extends over nearly all the torrid zone because there the annual variation of insolation is small. It also extends over large parts of the oceans of the southern hemisphere even up to quite high latitudes because the waters are only able to change their temperature with difficulty.

The areas of the most extreme ranges, over 70° F., are only found in the large land masses remote from the equator. Thus they are limited to the northern hemisphere as no great land masses are so situated in the southern. The greatest annual range occurs in the centre of Asiatic Siberia, where it approximates to 120° F. This is all in accord with what would be expected from what has been previously said with regard to absorption and radiation.

CHAPTER VI.

Water Vapour in the Atmosphere.

26. *General.**—Of all the constituents of the lower atmosphere water vapour is the most variable. At any time the total mass of it is very small compared with the mass of dry air, but the results accruing from that small amount are, from the meteorological point of view, amazingly great.

27. *Evaporation.*—The Molecular Theory of Matter states that matter is discrete, and not continuous, being made up of minute particles termed molecules. Further, the molcules are assumed to be in a state of incessant motion.

The results of the incessant motion vary, however, according to whether the matter is in the gaseous, liquid, or solid state. The molcules in the gaseous state are much more sparsely scattered than in either the liquid or solid state; collisions are much less frequent, and, consequently, the particles are much more mobile. Their impact on the walls of the containing vessel produces pressure on those walls. In the liquid state, the molecules, whilst by no means so mobile as in the gaseous state owing to the fact that they are closer together and that considerable forces are exerted between them, are yet sufficiently mobile to allow the liquid quickly to take up the shape of the vessel into which it is put. Whilst most of the molecules in the mass are not free to move far from their mean positions owing to the attractions of the surrounding molecules, yet some will attain to such a momentum that they will, when near the surface, break away from their neighbours and escape into space, thus reducing the volume of the original liquid. In course of time, continued repetitions of such escapes lead to the complete evaporation of the liquid. In thus breaking away from their neighbours, the escaping molecules do work which can only be performed at the expense of the heat energy in the remaining liquid. In consequence of this drawing out of heat, the remaining liquid is cooled and it is possible to find experimentally how much heat energy is necessary to evaporate 1 gram of the liquid. This quantity of heat is termed the latent heat of vaporisation and, in the case of water, it is 600 gram-calories. It is to be noted that raising the temperature of the liquid accelerates the motions of the molecules and thus increases the rate of evaporation. In the solid state, the molecules are much less mobile than in the case of either the gaseous or liquid state. This is shown by

* Much of the data in this, and the succeeding chapter, has been derived from the manuscript of a lecture on "The Water in the Atmosphere," by Dr. G. C. Simpson, F.R.S., Director of the Meteorological Office, London, who very kindly lent that manuscript to the present writer.

the low compressibility of solids as well as by the slow rate at which one solid will diffuse into another. It is a mistake to suppose, however, that there is no such phenomenon as evaporation in the case of solids. The smell of camphor, for example, is due to the direct breaking away of some of its molecules, and ice is also known to evaporate directly into the vapour state. The heat required to bring about this latter change, however, is exactly the same as though the ice were first changed into liquid water and then the liquid water into water vapour. The latent heat of vaporisation of ice is equal to the sum of the latent heat of liquefaction of ice and the latent heat of vaporisation of water.

But whether a solid or a liquid be evaporating, the number of molecules which leave each square unit of its surface per unit of time depends only upon the temperature, the number increasing with rise of temperature.

28. *Vapour Pressure.*—Let it be supposed that water is evaporating in a closed, vacuous space. The molecules that escape from the surface of the water accumulate in the space above the water as water vapour. The concentration of this water vapour goes on increasing but the molecules of it are also in a state of incessant motion, and some of them will plunge back into the liquid water from which they originally escaped. The number of the molecules which thus return to the liquid from the vapour increases as the concentration of the latter increases. After a certain interval of time, a point will be reached at which the number of molecules which return to the liquid in any given time is exactly equal to the number of molecules which leave the liquid in the same given time. The system is then in equilibrum and the vapour is said to be saturated. It is to be recognised, however, that the equilibrium is kinetic and not static. There is no state of rest; molecules continue to leave the liquid and molecules continue to return to the liquid; but as the number of each is equal for any given time, no visible result, one way or the other, can be produced.

Though in what has been said the space above the liquid water has been taken as being originally vacuous, it could be filled with air or any other gas and evaporation would continue just as before, and at the point of equilibrium, provided the temperature had not been altered, the same number of molecules would still leave the surface per unit of time.

When equilibrium is attained for any particular temperature, that is, when the vapour is in a saturated condition, there is a definite quantity of water vapour in each unit volume of the space above the liquid water, and this quantity is the same whether there be air in the space or not. This water vapour will exercise a definite pressure upon the walls of the vessel containing it by reason of the impacts of its molecules.

The same holds true for any other temperature; there will be at the point of equilibrium a definite quantity of water vapour, different for each temperature, in each unit volume of the space above the water, and this water vapour will exert a definite pressure entirely irrespective of the pressure of the surrounding air.

For each temperature, then, the actual amount of water vapour in the air above a flat water surface when that air is saturated with water vapour may be expressed either as a mass per unit volume or, and this is more convenient in practice, by the pressure it exerts. Tables have been prepared and are generally available giving these data. The lower the temperature the smaller the mass of water vapour per unit of volume and the lower the pressure exerted by that vapour.

29. *The Dew Point.*—From what has been already said, it will be seen that if air, only partially saturated with water vapour, be cooled, a temperature will be reached sooner or later at which the water vapour actually present will be sufficient to saturate that air. Any cooling beyond that point, called the "dew point," will cause some of the water vapour to condense in the form of liquid water.

30. *Absolute and Relative Humidity.*—At any moment, the air contains a certain quantity of water per unit volume, a quantity which varies from place to place. It may, or may not, be saturated. The actual amount of water vapour in the air is termed the absolute humidity of that air. It is most correctly expressed as a mass per unit volume, but, in practice, is more conveniently expressed by the pressure it exerts.

The important meteorological matter, however, is the relative humidity which may be defined as the ratio of the actual amount of water vapour present in the air to the amount which the same volume of air would hold if it were saturated. It is usually expressed as a percentage. At the dew point, the percentage is 100.

Relative humidity is a very variable meteorological element inasmuch as it depends not only upon the amount of water vapour present, but also upon the temperature of the air, which temperature is continually varying from place to place and from time to time.

31. *The Measurement of Relative Humidity.*—The instruments usually employed at meteorological stations for determining the relative humidity are the dry- and wet-bulb thermometers. These consist of two exactly similar thermometers placed in a Stevenson screen, which consists of a large wooden box with louvred sides. The screen protects the thermometers within from direct sunshine and the louvred sides permit of sufficient ventilation to ensure that the air within is a fair sample of the air without. Further, to obtain the true air

conditions, it is erected 4 feet above the ground in the most open, exposed position possible. The dry bulb shows the temperature of the air. The wet bulb is exactly similar to the dry-bulb thermometer except that its bulb is covered by a piece of muslin which is kept wet by means of conducting threads leading into a small vessel containing water.

If the outside air is not saturated, evaporation will take place from the muslin. Energy is needed to break down the inter-attractions of the particles during the evaporation. This energy is obtained at the expense of the heat of the adjacent surface, that is, the thermometer bulb which records a fall in temperature accordingly.

If the outside air is saturated already with water vapour, no evaporation takes place from the muslin; consequently, there is no fall of temperature recorded by the wet bulb and the two thermometers read the same. If the surrounding air is comparatively dry, that is, if it has a low relative humidity, much evaporation will take place from the wet bulb which will cause considerable cooling of that bulb, and hence there will be a large difference between the readings given by the two thermometers.

Theoretical formulæ have been proposed to obtain the relative humidity of the air from the respective temperatures indicated by the dry and wet bulb thermometers, but the phenomena occurring during the experiment are too complicated to lead to a simple yet adequate expression. Tables have, however, been constructed by other experimental means to show the relationship between the two temperatures and the humidity of the air and these tables are always used in practice.

Various instruments for automatically recording the relative humidity of the air from moment to moment have been devised. The best depend for their action upon the fact that the length of a human hair, which has been freed from fat by boiling in caustic soda or caustic potash, varies with the relative humidity of the air in which it is placed, getting longer with increase of humidity and shorter with decrease. A similar phenomenon is observed with spiders' webs which hang much more loosely when the relative humidity of the air is high than when it is low, and also with the catgut strings of musical instruments. Other materials contract when they absorb moisture, as, for example, rope; with which fact negligent campers in tents are sometimes made painfully aware.

If the human hair—a bundle is found more convenient in practice—be suitably supported, a pen attached to the middle of it may be made to mark the relative humidity upon a properly calibrated chart placed upon a drum which is kept revolving by clockwork. Such self-recording hair hygrometers are very useful, but require great attention, as the properties of hair are subject to slow changes, so that the same relative

humidity is not always shown with the same change in the length of the hair. Frequent settings against the relative humidities determined by a dry-and-wet bulb thermometer are, therefore, necessary.

32. *Other Considerations.*—In Sections 27 and 28 it was assumed that the surface of the water from which molecules were escaping was flat. This point is important, because the number of molecules which leave a surface depends upon whether that surface is flat or not. More molecules leave a convex surface than a flat one, and more molecules leave a flat surface than a concave one. The point has an important meteorological bearing inasmuch as water often appears in the atmosphere as drops either as rain drops or cloud particles.

Let it be imagined that in a closed vessel water vapour is in equilibrium with a flat water surface. Let it be imagined further that a drop of water be introduced into the space above the flat water surface. The drop is convex, and hence more molecules will leave each unit area of its surface per unit of time than leave each unit area of the flat water surface in the same time. But in the same unit of time the drop receives per unit area of its surface from the water vapour surrounding it just as many molecules as does each unit area of the flat water surface. That is to say, the drop in each unit of time receives less molecules than leave it. In other words, the drop is evaporating. The water evaporated from it will condense into the flat water surface, because it increases the number of molecules above that surface and thus destroys the state of kinetic equilibrium originally existing between the ingoing and outgoing particles passing through that surface.

If, however, there is no flat water surface present, and if condensation on to any body is not possible, the vapour pressure will rise above its normal saturation value until the vapour returns to the drop the same number of molecules per unit of time as it receives from it. Equilibrium will then be established between the drop and the vapour, but the pressure of the latter will be above its normal saturation value. Therefore, in order for drops to be in equilibrium with surrounding water vapour, super-saturation of the latter is necessary.

The smaller the radius of the drop the greater must be the amount of super-saturation of the surrounding vapour to prevent the drop from evaporating. It follows from this, too, that the smaller the drop the greater must be the amount of the super-saturation of the surrounding vapour if that vapour is to condense at all upon the drop. Calculations made by Wegener* show that the drops must be extremely small if the super-saturation of the surrounding vapour necessary to preserve equilibrium is to be appreciable. The drops constituting ordinary cloud particles have a radius of 0·001 cms., and for

* A. Wegener.—Thermodynamik der Atmosphare, p. 71.

this size the super-saturation necessary for equilibrium is almost negligible, being only 0·00012 per cent.; but for smaller drops the super-saturation if equilibrium is to be preserved is comparatively large, a factor which must weigh considerably in the initial stages of rain and cloud formation.

33. *Dew.*—About sunset the temperature of the ground, and hence of the air in contact with the ground, begins to fall owing to the increasing effect of radiation. The falling temperature of the air means that its capacity for water vapour decreases, that its relative humidity increases, and that soon the air near the ground is brought very near to its saturation point. From this time onwards the further cooling of the ground by radiation lowers the temperature of the air gradually, and the dew point, the point of saturation, is soon reached. But not only is the air cooling, but also all bodies which can radiate to the clear sky. The loss of heat from all bodies is practically the same, but those bodies which are good conductors of heat and which are in good thermal contact with the ground are able to draw from the supplies of heat contained in the latter, and thus, despite the radiation, their temperatures will not fall very much. On the other hand, bodies which are bad conductors of heat are not able to draw appreciably upon those supplies of heat, and hence, not being able materially to compensate for the loss of heat due to radiation, their temperatures will fall. Rocks are a good example of the former class, and grasses of the latter.

Further, compared with air, all solid bodies are good radiators of heat. Consequently the temperature of grasses, small shrubs, and the like, may fall below the dew point of the air before the air itself reaches that dew point. Hence these solid bodies will chill the air immediately in contact with them to below its dew point, and water will be condensed from that air upon them. This theory of the formation of dew was put forward by Wells in 1818. Aitken has amplified this theory by showing that much of the water deposited as dew rises from the damp ground by capillary action, and that some is actually exuded by the plants themselves.

Dr. G. C. Simpson,* in the following, states the conditions which affect the formation of dew. He says:—"Any condition "which prevents the cooling of the air or of the bodies on "which dew usually deposits is detrimental to the formation "of dew. For example, a cloudy sky prevents radiation; a "high wind equalises the temperature of the air and of the "bodies over which it passes, and by mixing up large quan- "tities of air prevents a local fall of temperature near the "ground. There are four conditions absolutely necessary to

* Dr. G. C. Simpson, F.R.S. Manuscript of lecture on "The Water in the Atmosphere" previously referred to in section 26.

" the formation of dew, (1) a good radiating surface, (2) a still " atmosphere, (3) a clear sky, and (4) thermal insulation of the " radiating surface. It is also necessary if there is to be a " copious deposition of dew that the ground should be warm " and moist or there should be some other source of water " vapour to maintain the supply of moisture to the surface " layers of air. Dew is generally formed during all clear calm " nights in situations where the air is naturally moist, for, " example, in marshy country and along the banks of rivers."

34. *Frost.*—When the dew point is lower than 32° F., the water vapour condenses as ice in the form of hoar frost. In the British Isles the dew point is not often likely to be below 32° F. in the late spring, the summer, or the early autumn. In the remaining part of the year the main factors which an observer, anxious to know whether frost is to be expected, has to consider are the following:—

(*a*) The likely state of the sky face between sunset and sunrise.

(*b*) The likely velocity of the wind during the same period.

(*c*) Local peculiarities of situation.

It is assumed that the observer is propounding his question just before the time of sunset.

A clearing sky and a falling wind are helpful to the formation of frost, as would be expected from what has already been said about dew formation, because a clear sky greatly favours the cooling of the earth's surface by radiation as has been previously explained, and because calms or very light winds keep any particular sample of the air in contact with the cooling ground for a considerable period, and hence that air is given the best opportunity to become cooled itself.

The effect of situation is that air on the hill-tops becomes cooled more quickly than does the air in the valleys owing to the greater radiations from the hill-tops (*see* section 17). This means that cold air trickles down the hill slopes by gravitation and settles in the valleys. These pools of cold air thus formed in the valleys are all in favour of frost development with the result that, as a rule, frost becomes more severe as one goes down from the hills into the valleys, and that hollows in the hill sides are colder than the unindented slopes.

A big difference in the dry- and wet-bulb readings at sunset is also a herald of frost provided that the other conditions are favourable, inasmuch as that means that the air is very dry, and that, consequently, it will need to be cooled considerably, probably to below 32° F., to reach its saturation point. The other conditions, the clearing sky and the falling wind, will bring about the maximum cooling; this maximum cooling, in conjunction with the original very low relative humidity as shown by the big difference noticed between the dry- and wet-

bulb readings, ensures that when the saturation point is reached and passed, it will be frost deposited and not dew.

The American practice of "smudging" to protect crops from the damage caused by frost is interesting, because it is a practical application of a general principle already stated. It has been said (*see* section 14) that clouds prevent the earth's surface from cooling so much as otherwise it would because they reflect back some of the radiation to it. "Smudging" consists in building a smoky fire on the windward side of the crops to be protected so that a thick layer of smoke drifts over them. The layer of smoke acts just as a cloud in a similar position would do; it reflects back much of the radiation to the earth, and thus maintains the surface temperature at a higher level than that of the non-smoke screened surfaces in the neighbourhood.

CHAPTER VII.

Fog and Mist.

35. *General.*—In section 33 it was shown that dew is a direct deposition from the water vapour in the air upon solid bodies due to the fact that the temperature of the latter falls below the dew point of the air, whilst the air itself has a temperature above that dew point. If the temperature of the air itself falls below the dew point, then an entirely different phenomenon, the formation of mist or fog, occurs.

36. *The Necessity of a Nucleus for Condensation.*—To form a water drop in the atmosphere, the basis of mist or fog formation, there must already be present some nucleus upon which the water may form. It was formerly thought that dust particles formed the nuclei for condensation, but very careful work by Assmann,* Wegener,† and Wegand‡ has shown that dust in the ordinary sense of the term is not sufficient. The results of their work point to the fact that the nuclei, whatever they are, begin to attract water to themselves before the air around them is saturated, begin to attract water, in fact, when that air is relatively dry. The nuclei seem to have some natural affinity for water and are nuclei for condensation just because of that property.

Substances are known which have such a natural affinity for water. They are termed "hygroscopic," and examples of

* Assmann.—Meteorologische Zeitschrift, 1885, p. 41.
† Wegener, A.—Meteorologische Zeitschrift, 1910, p. 357.
‡ Wegand.—Meteorologische Zeitschrift, 1913, p. 10.

them are calcium chloride, sodium chloride (common salt), and sulphuric acid.

Meteorological opinion now holds that condensation does not begin upon dust particles in the ordinary sense but upon particles of hygroscopic substances occurring in the air. The nature of these particles is still open to some doubt, but it seems certain that salt, derived from sea spray or from the drying sand of the shore, constitutes a large proportion of them. Household and factory chimneys, too, belch forth great quantities of such nuclei-forming material, the chief of which is sulphur dioxide which, when illuminated by sunlight, becomes a highly hygroscopic substance capable of causing condensation in unsaturated air. The activities of volcanoes constitute another means whereby the atmosphere is supplied with nuclei-forming material.

Nuclei-free air can be prepared experimentally in the laboratory and C. T. R. Wilson has shown that air in this condition can be dynamically cooled until a state of fourfold super-saturation is reached without condensation of the water vapour in it occurring; in other words, the air may be cooled a long way below its dew point without liquid water being deposited. But this hardly concerns the student dealing with the free atmosphere for no sample of that has yet been found, even at heights, to be free from nuclei, which is not surprising when what has been said about the sources of those nuclei is remembered.

37. *Some Lessons from Smoke Aggregations.*—It is instructive to consider some questions arising with regard to aggregations of smoke, especially with regard to the atmospheric conditions which aid in the maintenance of the smoke aggregations once they are formed, for similar conditions may apply to the maintenance of fogs, at least in part.

Imagining, then, that a smoke aggregation is formed in any way, say by the belching forth of several neighbouring factory chimneys, there are two ways in which dissipation of it may be brought about. Those two ways are—

(*a*) A wind, or
(*b*) Upward convection currents.

It is surprising how small a wind velocity is sufficient to disperse smoke, and it would appear that for the maintenance of any considerable smoke in the neighbourhood of the chimneys a calm is practically necessary.

The question of upward convection currents presents points of interest. Let it be assumed that a mass of air is carried upwards from one layer A to a higher layer B. As it rises, it gets into regions of less pressure. Consequently it expands and the expansion causes a fall in temperature. This fall in temperature has already been stated (*see* section 22) to be equal to 1·6° F. in 300 feet. It is clear,

therefore, that if the upward temperature gradient of the surrounding air be less than 1·6° F. per 300 feet, the rising mass of air will, when it arrives at layer B, find itself surrounded by air which is warmer than itself. Consequently, the mass of air will have no further tendency to rise, but, on the contrary, a tendency to descend. Therefore, an atmosphere in which the vertical temperature gradient is less than 1·6° F. per 300 feet will tend to stop upward convection currents. The smaller the vertical temperature gradient is, the more effective does this tendency to stop upward convection currents become. If the vertical temperature gradient be actually reversed, that is, if an inversion of temperature exists, the tendency reaches its maximum effectiveness and no currents are likely to rise at all.

The atmospheric conditions, then, favouring the maintenance of a smoke aggregation once it is formed are (1) the absence of wind and (2) a vertical temperature gradient in the air of value less than 1·6° F. per 300 feet, with this latter condition reaching its maximum efficiency if an actual inversion of temperature exist.

38. *Fogs.*—Fogs are due to the condensation of the water vapour of the atmosphere upon nuclei existing in that atmosphere. The condensation is due in most cases to cooling of the air below its dew point by reason of it radiating either to the night sky or to the cold ground.

One factor, then, in the formation of fogs appears to be the cooling of the surface underneath the air in which the fog appears. But the differences of land and sea in regard to such cooling need to be borne in mind. The land surface is subject to great changes of temperature due to its great powers both of absorption and radiation of radiant energy. The extent of these changes depends, as has already been said, upon the cloudiness of the sky. Sea surfaces, on the other hand, have a very much more limited range of temperature; and, in fact, the diurnal variation is sometimes almost inappreciable.

The thick "pea-soup" fogs, characteristic of London and other large industrial centres, require some mention. The atmosphere in those centres is full of actual particles of carbon and the like emitted in the smoke from the many chimneys. The water forming the basis of the fog is deposited upon the small hygroscopic particles, the nuclei, already discussed. When the drops are once formed they absorb the carbon and dust particles and, in consequence, become dark. The fog would form without the black smoke particles but it would be a white fog and not a black one. Smoke abatement would therefore not do away with fogs, but it would do much to make the fogs occurring white and not black, and to this extent is worthy of much consideration.

39. *Fog at Sea.*—The famous fogs of the Newfoundland Banks are a typical example of the formation of fog at sea.

In the region of that island, the temperature of the sea water is kept low by reason of cold currents from the Arctic flowing into it. In the summer time, it is surrounded on all sides except the north by considerably warmer regions. Air blowing across the Banks, then, from south, east, or west, is cooled by contact with the cold waters. If the air blowing in is nearly saturated with water vapour, the cooling produced is sufficient to bring it down to its saturation point and water condenses around the nuclei in the air and a fog is formed. This is especially the case with southerly winds.

40. *Fog on Land.*—Water-drop fogs are formed on land under those conditions which promote great cooling of the land surface with which the air is in contact. Those conditions are—

(*a*) a light wind or a calm ;
(*b*) a mainly clear night sky.

The first condition acts by keeping the mass of air long enough in close proximity to the surface of the ground to enable it to become thoroughly cooled, and the second by permitting radiation to space to be abundant.

41. *Mist.*—It is a matter of some difficulty to distinguish between fog and mist. The practical method of differentiation is that based on how far one can see ; if the distance which can be seen is under a certain limit the obscurity is termed fog ; if over, mist.

Mists and fogs are similar in many respects to clouds, but there is one fundamental difference which makes it very undesirable to describe them as " clouds near the ground." As will be seen later (Chapter IX.), clouds are nearly always caused by temperature changes due to adiabatic cooling when air ascends. This means that clouds are due to pressure changes in the mass of air itself. Pressure changes, however, play very little part in the formation of mists and fogs. The lowering of temperature which causes these latter phenomena is due, not to pressure changes, but, in the main, to actual radiation from the ground.

42. *Haze.*—Further difficulty is introduced by haze. Haze may be due to smoke or dust due to the neighbourhood of a town, or to dust raised from the ground by wind, or to irregularities of density in the atmosphere and consequent irregular refraction of the light such as occurs over the flame of a bunsen burner. It seems well to limit the use of the term " haze " to those occasions when the air is dry, and to use " mist " when the air is wet. The dividing line is generally taken as 80 per cent. relative humidity, but a skilled observer is usually able to see if the obscurity is caused by dust particles or irregular refraction, or by condensed water vapour.

43. *Visibility.*—Visibility, with which haze, mist, and fog are intimately connected, is measured at meteorological stations by locating a number of objects, such as church towers, buildings, and the like, within definite limits of distance and determining at the time of observation which object can be seen whilst the one at a greater distance just beyond it cannot be seen. At night, distant lights are similarly used.

The whole subject is, however, an exceedingly difficult one. The state of visibility, of good or bad seeing, depends upon a great number of factors. It depends not only upon the meteorological conditions prevailing at the time but also on the conditions which have gone before. It depends, also, upon the geographical location of the place with regard to sources of dust. The structure of the upper air, too, is important, especially with regard to temperature. Much, too, depends upon the direction and velocity of the surface wind.

Inversions of temperature near the ground are a cause of bad seeing as they prevent upward convection currents (*see* section 37). Attempts, too, have been made to correlate the various types of pressure distribution (*see* Part II.) with visibility, but it cannot be said that these have met with any conspicuous success.

CHAPTER VIII.

Clouds.

44. *Classification.*—Cloud phenomena are "infinite in their variety." Certain types may be selected as standard, but even a short period of observation reveals that the types selected do not exhaust the clouds actually appearing. All manner of intermediate types occur. The series of clouds is continuous. Nevertheless it is necessary to have some classification.

Luke Howard in 1803 was the first to propose some such classification. He distinguished three principal cloud forms—

(1) Cirrus cloud (which included all types of fibrous or feathery appearance).
(2) Cumulus cloud, having rounded tops and being generally lumpy in appearance.
(3) Stratus cloud, applying to all clouds lying in level sheets.

This classification suited the purposes of those comparatively early times when accurate observation was in its infancy. In course of time, however, attention was directed to smaller degrees of difference, and the need for a more detailed classification became apparent.

45. *The International Classification.*—Matters came to a head in 1894, and at a meeting of the International Meteorological Committee held in that year at Upsala the publication of a cloud atlas, which should at the same time be a classification, was entrusted to MM. H. H. Hildebrandsson, A. Riggenbach, and L. Teisserenc de Bort. The first edition of the atlas was published in 1895, and a new edition, incorporating the improvements suggested at the International Meteorological Conference at Innsbruck in 1905, appeared in 1910.

This classification, consisting of 10 main types backed by such international authority, must be regarded as the standard until some similar gathering introduces alterations..

46. *International Definitions and Descriptions of Cloud Forms.*—The international definitions and descriptions of the 10 types of cloud forms* are now given. Those which follow are those appearing in the "Observer's Handbook" issued by the Meteorological Office, London, 1919 edition. In that publication the translation into English has been altered in certain respects from that which appears in the English version of the introduction to the "International Cloud Atlas" in order to represent more closely the original French. The abbreviations in brackets after the names of the clouds are the contractions agreed upon internationally, and no others should be used.

"(1) †**Cirrus (Ci.).—Detached clouds of delicate appearance, fibrous (threadlike) structure and feather-like form, generally white in colour.** Cirrus clouds take the most varied shapes, such as isolated tufts of hair, *i.e.*, thin filaments on a blue sky, branched filaments in feathery form, straight or curved filaments ending in tufts (called **cirrus uncinus**), and others. Occasionally cirrus clouds are arranged in bands, which traverse part of the sky as arcs of great circles, and as an effect of perspective appear to converge at a point on the horizon, and at the opposite point also if they are sufficiently extended. Cirro-stratus and cirro-cumulus also are sometimes similarly arranged in long bands.

"(2) **Cirro-Stratus (Ci.-St.).—A thin sheet of whitish-cloud; sometimes covering the sky completely and merely giving it a milky appearance; it is then called cirro-nebula or cirrus haze; at other times presenting more**

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* "Atlas International des Nuages" (The International Cloud Atlas). Publié conformement aux décisions du Comité, par A. Hildebrandsson et L. Teisserenc de Bort, Membres de la Commission des Nuages. Seconde edition. Gauthier-Villars. Paris, 1910. The definitions and descriptions are published in the atlas in French, English, and German.

† It may be noted that the outline of the sun is visible, and his rays cast a shadow in spite of the presence of clouds of these types, unless the clouds and the sun are both low down on the horizon.

or less distinctly a fibrous structure like a tangled web. This sheet often produces halos around the sun or moon.

"(3) *Cirro-Cumulus (Ci.-Cu.) (Mackerel Sky). —**Small rounded masses or white flakes without shadows, or showing very slight shadow; arranged in groups and often in lines.** French, *Moutons*—German, *Schäfchen-wolken.*

"(4) **Alto-Stratus (A.-St.).—A dense sheet of a grey or bluish colour, sometimes forming a compact mass of dull grey colour and fibrous structure.** At other times the sheet is thin like the denser forms cirro-stratus, and through it the sun and the moon may be seen dimly gleaming as through ground glass. This form exhibits all stages of transition between alto-stratus and cirro-stratus, but according to the measurements its normal altitude is about one-half of that of cirro-stratus.

"(5) **Alto-Cumulus (A.-Cu.).—Larger rounded masses, white or greyish, partially shaded, arranged in groups or lines, and often so crowded together in the middle region that the cloudlets join.** The separate masses are generally larger and more compact (resembling strato-cumulus) in the middle region of the group, but the denseness of the layer varies and sometimes is so attenuated that the individual masses assume the appearance of sheets or thin flakes of considerable extent with hardly any shading. At the margin of the group they form smaller cloudlets resembling those of cirro-cumulus. The cloudlets often group themselves in parallel lines, arranged in one or more directions.

"(6) **Strato-Cumulus (St.-Cu.).—Large lumpy masses or rolls of dull grey cloud, frequently covering the whole sky, especially in winter.** Generally strato-cumulus presents the appearance of a grey layer broken up into irregular masses and having on the margin smaller masses grouped in flocks like alto-cumulus. Sometimes this cloud-form has the characteristic appearance of great rolls of cloud arranged in parallel lines close together. (**Roll-cumulus** in England, **Wulst-cumulus** in Germany.) The rolls themselves are dense and dark, but in the intervening spaces the cloud is much lighter and blue sky may sometimes be seen through them. Strato-cumulus may be distinguished from nimbus by its lumpy or rolling

* It may be noted that the outline of the sun is visible, and his rays cast a shadow in spite of the presence of clouds of these types, unless the clouds and the sun are both low down on the horizon.

appearance, and by the fact that it does not generally tend to bring rain.

"(7) **Nimbus (Nb.).—A dense layer of dark, shapeless cloud with ragged edges from which steady rain or snow usually falls. If there are openings in the cloud an upper layer of cirro-stratus or alto-stratus may almost invariably be seen through them.** If a layer of nimbus separates in strong wind into ragged cloud, or if small detached clouds are seen drifting underneath a large nimbus (the **"Scud,"** of sailors), either may be specified as **fracto-nimbus** (Fr.-Nb.).

"(8) **Cumulus (Cu.) (Wool-pack or Cauliflower Cloud).— Thick cloud of which the upper surface is dome-shaped and exhibits protuberances while the base is generally horizontal.** These clouds appear to be formed by ascensional movement of air in the daytime which is almost always observable. When the cloud and the sun are on opposite sides of the observer the surfaces facing the observer are more brilliant than the margins of the protuberances. When, on the contrary, it is on the same side of the observer as the sun it appears dark with bright edges. When the light falls sideways, as is usually the case, cumulus clouds show deep shadows.

"True cumulus has well-defined upper and lower margins; but one may sometimes see ragged clouds—like cumulus torn by strong wind—of which the detached portions are continually changing; to this form of cloud the name **Fracto-Cumulus** may be given.

"(9) **Cumulo-Nimbus (Cu.-Nb.). The Thunder Cloud; Shower Cloud.—Great masses of cloud rising in the form of mountains or towers or anvils, generally having a veil or screen of fibrous texture (false cirrus) at the top and at its base a cloud-mass similar to nimbus.** From the base local showers of rain or of snow, occasionally of hail or soft hail, usually fall. Sometimes the upper margins have the compact shape of cumulus, or form massive heaps round which floats delicate false cirrus. At other times the margins themselves are fringed with filaments similar to cirrus clouds. This last form is particularly common with spring showers. The front of a thunderstorm of wide extent is frequently in the form of a large low arch above a region of uniformly lighter sky.

"(10) **Stratus (St.).—A uniform layer of cloud like fog but not lying on the ground.** Plate I. The cloud layer of stratus is always very low. If it is divided into ragged masses in a wind or by mountain tops, it may be called **Fracto-Stratus.** The complete absence of detail of structure differentiates stratus from other aggregated forms of cloud.

"The following remarks are added in the international atlas as instructions to observers:—

"(*a*) In the daytime in summer all the lower clouds assume, as a rule, special forms more or less resembling cumulus. In such cases the observer may enter in his notes '**Stratus-** or **nimbus-cumuliformis.**'

"(*b*) Sometimes a cloud will show a mammillated surface and the appearance should be noted under the name **mammato-cumulus.**

"(*c*) The form taken by certain clouds, particularly on days of sirocco, mistral, föhn, etc., which show an ovoid form with clean outlines and sometimes irisation, will be indicated by the name **lenticular,** for example: **cumulus lenticularis, stratus lenticularis** (Cu.-lent., St.-lent.).

"(*d*) Notice should always be taken when the clouds seem motionless or if they move with very great velocity.

"A definition of the lenticular form of cloud is necessary. It may be put into the following words:—

"(11) **Lenticular Cloud Banks.—Banks of clouds of an almond or airship shape, with sharp general outlines, but showing, on close examination, fretted edges, formed of an ordered structure of cloudlets similar to alto-cumulus or cirro-cumulus, which is also seen in the bank itself when the illumination is favourable.** Sometimes the body of the cloud bank is dense, and the almond shape is complete, fore and aft, but sometimes the bank thins away from the forward edge to clear sky within, so that the bank presents the appearance of a horse-shoe seen in perspective from below at a great distance. The bank appears nearly or quite stationary, while the cloudlets move rapidly into it at one side and away from it at the other."

47. *Other Considerations.*—The 10 main types of international classification are subdivisible into—

(*a*) Cloud sheets.
(*b*) Heap clouds.

Cumulus and cumulo-nimbus are heap clouds and the remaining types cloud sheets. The heap clouds are

characterised by considerable vertical structure but do not form horizontal layers. The cause of their formation, ascensional movement of air, will be treated in the next chapter. The height of heap clouds is very variable. It has been estimated that the mean height of their bases is approximately 4,500 feet, but they are often found much lower, and the height of their summits varies from about 6,000 feet up to even 25,000 feet.

Cloud sheets, on the other hand, are characterised more by horizontal extension than by considerable vertical structure. Sometimes the sheets have breaks in them, sometimes they have not. Quite often, indeed, the sheets are represented by just a few isolated clouds in a mainly blue sky. The sheets vary considerably in thickness and, often, the sky shows several cloud sheets or layers existing at different levels at the same time.

The height of cloud sheets is also very variable. Cirrus, cirro-stratus and cirro-cumulus are generally above 25,000 feet; alto-stratus and alto-cumulus are generally between 10,000 and 25,000 feet; and strato-cumulus, nimbus, and stratus are generally below 7,000 feet.

Cirrus, cirro-stratus, and cirro-cumulus clouds are composed of ice crystals. It is important to notice that halos only occur in these very high clouds, inasmuch as halos are an optical phenomenon due to regular refraction of the light of the sun or moon as it passes through ice crystals. This point will occur again later in connection with the forecasting of weather and with weather lore.

48. *General.*—There is no royal road to a knowledge of cloud forms except the strenuous one of diligent observation of the sky face on as many occasions as possible, together with a careful comparison of what is observed with the descriptions of cloud forms already given. An atlas of cloud forms, ready at hand, is a very useful aid.

Such a study will be found at once delightful and useful: delightful because clouds are the main component of the variety and exquisite beauty of the sky face, and useful because, as will be seen later, it affords most valuable information to the forecaster anxious to know what the weather is likely to be. Clouds are alike beautiful and significant, and a study of them is confidently recommended to all.

CHAPTER IX.*

The Formation of Clouds, Rain, Hail and Snow.

49. *Condensation by Dynamical Cooling.*—This is the chief, and perhaps, the only cause† of cloud making. In all cases where a vertical or obliquely ascending motion is given to air, the air rises into regions of diminishing pressure. Such diminishing pressure upon the rising mass of air means that that air expands. As has been already stated, this expansion takes place adiabatically; that is, that considering the interior of the rising mass of air, no heat is either given to that interior or taken from it. Such adiabatic expansion is necessarily accompanied by cooling inasmuch as expansion means that work must be done in pushing back the surrounding air and that the energy necessary for the accomplishment of this work must come from the internal supplies held by the air in the rising mass. Such subtraction of energy from the molecules of the air in the mass means that the amplitude of vibration of those molecules is diminished. This, in its turn, means that cooling takes place in the interior of the ascending air.

The ascending air, then, merely because of its elevation, cools. The rate of the cooling (*see* section 22) due to this cause is 1·6° F. in every 300 feet of ascent. The temperature gradient upward of the surrounding air is, generally, about 1° F. in the same number of feet. This means that the rising air loses 0·6° F. for every 300 feet rise compared with the surrounding air. In a longer or shorter time, then, that rising air will arrive at such a height that its temperature, originally greater than its surroundings, becomes equal to that of its surroundings and no further ascent will then take place through the ordinary processes of convection.

Before this position of comparative equilibrium is reached, the ascending air may have cooled to its dew point. The nuclei present, however, may be so small that condensation cannot at once take place as super-saturation would be required to maintain the drops formed. The air, then, continues to rise

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* Once again in this chapter as in Chapters VI. and VII. the writer is very greatly indebted to the manuscript of a lecture on "The Water in the Atmosphere," by Dr. G. C. Simpson, F.R.S., Director of the Meteorological Office, London, kindly lent to him by the author.

† Wegener, in Chapter 16 of his "Thermodynamik der Atmosphare," gives the reason for this view.

until it is sufficiently super-saturated to allow of water being deposited on the small drops. The moment, however, that water is thus deposited, the drops, by reason of their increase in size, require a less super-saturation. A small drop in super-saturated air is, in fact, in a state of unstable equilibrium; the moment its size is increased at all, water is deposited upon it until it reaches such dimensions that there is practically no super-saturation in the surrounding air for the amount of super-saturation necessary for equilibrium decreases rapidly with increasing size. It has already been stated (*see* section 32) that cloud particles, as shown by direct measurement, have a radius of about 0·001 cms. and that drops of this size only require 0·00012 per cent. super-saturation of the surrounding air for equilibrium. This super-saturation is practically negligible and it may be said therefore that the air in a cloud is not in a state of super-saturation; but the initial super-saturation often necessary before condensation actually begins is noteworthy. It is not likely that there is ever much more than 1 per cent. of super-saturation.

As soon as condensation has actually begun, further deposition will continue upon the drops so long as the air current continues to ascend. The drops will thus increase in size until they fall as rain.

50. *The Fall of Water Drops through the Air.*—Some consideration of the laws governing the fall of water drops through the air is necessary before the actual formation of rainfall is treated.

In a vacuum, all bodies fall at the same rate with a constant acceleration. When, however, bodies fall through a resisting medium, such as air, they do not continually increase in velocity but only increase until the air resistance is exactly equal to the weight of the falling body under consideration, when the latter thenceforward continues to fall at a constant speed. This speed is not strictly uniform but decreases with the increasing density of the air in the lower layers.

The rate at which a rain-drop falls depends upon its size. The steady speed ultimately attained is called the "terminal velocity" and Lenard has prepared the following table* (Table II) showing how the terminal velocity in still air varies with the size of the drops.

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* Extracted from the "Meteorological Glossary" (4th issue): Meteorological Office, London.

TABLE II.

Terminal Velocities of Water Drops falling in Air.

Diameter of Drop.		Terminal Velocity.		Diameter of Drop.		Terminal Velocity.	
mms.	ins.	metres/sec.	miles/ hour.	mms.	ins.	metres/sec.	miles/ hour.
0·01	0·0004	0·0032	0·007	3·0	0·118	6·9	15·4
0·1	0·0039	0·32	0·71	3·5	0·138	7·4	16·5
0·5	0·020	3·5	7·9	4·0	0·157	7·7	17·2
1·0	0·039	4·4	9·8	4·5	0·177	8·0	17·9
1·5	0·059	5·7	12·6	5·0	0·200	8·0	17·9
2·0	0·079	5·9	13·2	5·5	0·216	8·0	17·9
2·5	0·098	6·4	14·3				

The frictional resistance offered by air to a drop depends upon the relative motion of the two. It does not matter whether the air be still and the drop moving, or vice versa, or whether both are moving with different velocities. The terminal velocities given in Tables II may be looked upon, therefore, as the velocities with which air must be moving vertically upward to keep drops of the diameters stated floating, without rising or falling. Lenard, in fact, actually obtained his results from experiments with vertical air currents and drops of known size.

The important fact to notice is that the terminal velocities do not increase indefinitely with the size of the drops, but that when the drops attain to a certain diameter the terminal velocity remains constant at 8 metres per second (25 feet per second or 17·9 miles per hour) for further increases in size.

This is due to the fact that the drops become deformed, flattening out horizontally so that the air resistance is increased. For diameters greater than 5·5 mms. (0·216 ins.) the deformation becomes so great that the drops break up before the terminal velocity of 8 metres per second is reached.

It follows, therefore, that no rain can fall through a current of air ascending at a greater velocity than 8 metres per second. In upward currents of velocity greater than that limit, the drops are either carried up intact or after being broken up into smaller drops.

It is known that upward currents having such velocities do exist from time to time. The drops formed in such currents are afforded ample opportunity to increase in size, and it is therefore probable that such currents carry up with them great quantities of water. The large drops so formed have two ways of reaching the earth; first, by being carried on into the outflow of air above the region of violent convection, or second, by a sudden stoppage of the upward convection. Such sudden

stoppages are probably the cause of the very heavy rains experienced in what are termed, "cloud bursts."

51. *The Formation of Rain.*—It is pertinent at this point to outline briefly the process which causes rain. When the wind circulation is such that the air currents flow towards a common centre, as is the case in cyclones (*see* Part II.), the only way by means of which the air can escape is by upward motion. Its ascent is accompanied by the phenomena of expansion and cooling. When the dew point is reached condensation commences upon the nuclei present. The drops formed at first are very small, probably of the order diameter—0·002 mms., and thus they are carried upward with the rising air. The further ascent means further cooling and more condensation of water upon the drops, thus increasing their size. When the diameter reaches 0·2 mms., the drops are falling relatively to the air at the rate of about 1 metre per second, which is more rapid that air currents normally rise and thus the cloud begins to rain.

52. *Condensation at Temperatures below the Freezing Point.*—In a consideration of condensation occurring at temperatures below the freezing point, there are two cases to examine:—

(*a*) when the condensation commences before the temperature falls below the freezing point;

(*b*) when condensation only commences after the freezing point has been passed.

The first of these two cases comes into operation when the ascending currents continue until the temperature of 32° F. (the freezing point) is reached and passed, the dew point being above 32° F. The point arises as to whether the water drops freeze after the freezing point is passed and, if they do, what form do they take?

Now, observations have been made in balloons and on mountain tops, and these have revealed the fact that water drops, certainly in the liquid form, can co-exist with temperatures, as low as 0° F. It is clear, then, that small drops can be super-cooled a long way without solidifying. Exactly how far such super-cooling can be carried is not known but, in any case, the state is one of instability. If, for any reason, a few drops do solidify, they find themselves at once in a greatly super-saturated atmosphere and condensation in the solid form rapidly takes place upon them. The equilibrium over the other drops is, at the same time, destroyed and the water drops rapidly evaporate, the water distilling from the drops on to the ice particles.

Every big cloud formed as a result of an upward current of air is divisible into three parts. First, there is the lowest layer where the cloud particles are in the form of liquid water drops; next, there is a region where the cloud particles are still water drops but in which the latter are more or less super-cooled;

and thirdly, there is the highest region of the cloud where the drops are frozen into ice, this region being usually called the "snow region."

53. *Hail.*—There is no sharp line of demarcation between the snow region and the region of super-cooled water. For quite a distance ice crystals and super-cooled water are co-existing. If a super-cooled water drop impinge against an ice crystal it at once solidifies and, at the same time, imprisons a little air. Consequently, the ice crystal increases in size and will begin to fall if the velocity of the ascending air be not too great. But as it falls it passes through the entire length of the region of super-cooled water with the result that it grows still more, and imprisons more air, arriving at the bottom of the super-cooled region as a ball of soft ice without any definite crystalline structure.

If the velocity of fall of the ball through the super-cooled region has been at all great, it arrives in the region where the temperature is just 32° F. with its own temperature lower than 32° F. Consequently any further falling means that water is directly deposited upon it, which water covers the surface of the ball with a uniform layer of liquid which quickly freezes as a hard, transparent covering with little or no air imprisoned in it. Finally the ball falls out of the base of the cloud as a hailstone.

Hailstones cut open to reveal their structure show the soft core of white ice and the hard transparent layer of clear ice which are in conformity with the theory of formation which has been outlined.

But there is a further addition to be made to the life story of large hailstones. An ascending current of air is not steady but composed of increases and decreases, of gusts and comparative lulls. A hailstone which has reached the lower part of the cloud may meet one of the gusts and be blown upwards and thus be forced to go through the whole process again, a layer of white, soft ice being formed around the previous transparent layer, and another transparent layer being added around that. Further repetitions of the carrying up add additional layers. A hailstone, if cut open when it finally falls after such a protracted history, would show several concentric layers of white and clear ice. Such hailstones have frequently been found.

Two conditions, then, seem essential for the production of large hailstones:—

(*a*) the clouds must possess great vertical structure so that the three regions—the water region, the super-cooled region, and the snow region—are well developed.

(*b*) there must be present ascending currents of air of considerable violence so that the hailstones, once formed, may be whirled up and down several times.

Warm regions best favour the production of these conditions for there the high temperature reached by the ground during the hours the sun is well above the horizon favours the formation of violent ascending currents and, at the same time, condensation starts at comparatively high temperatures, thus making the water and the super-cooled regions of the clouds to be of extensive depth.

54. *Soft Hail.*—If the point where the temperature is just 32° F. (the freezing point) be near to the ground, the hailstones in falling from that point to the ground do not have much water deposited on them and so the hard, transparent layers (*see* section 53) covering the soft, white core are more or less absent and the hail arrives at the ground as just the original soft white ice. It is then known as "soft hail." It is assumed that there are no violent upward currents present so that the hail is not subjected to rapid whirlings up and down.

55. *Further Consideration of Condensation at Temperatures below the Freezing Point.*—In section 52 it was stated that there are two cases of condensation occurring at temperatures below the freezing point. The first of these two cases has already been considered in sections 52–54. The second case is when the condensation only commences after the freezing point has been passed.

Dr. Simpson approaches the subject from a study of fogs and iridescent clouds seen in the Antarctic.* He describes one occasion, for example, on which he was enveloped in a fog during sunshine. A white bow was seen on the fog opposite the sun in the position usually occupied by a rainbow. The formation of such a bow, however, could only be explained on the assumption that the fog was composed of small drops. The temperature of the air was — 21° F. Experiments on iridescent clouds also led him to the conclusion that the effects observed in them, as well as in the fog, could only be produced by the refraction of light by small spheres. Iridescent clouds, however, are only formed in very low temperatures in polar regions or at very high elevations in temperate ones. His general conclusion then was, that super-cooled water exists at much lower temperatures than is usually thought possible.

It is clear that the air in which the water drops formed to give the effects already referred to was far below the freezing point in temperature. The problem is how water drops can form at such a temperature.

Dr. Simpson† states that the solution of the problem is to be found in the chemical fact enunciated in the following quotation‡:—"As has been shown time and again, when a new

* *See* Quarterly Journal of the Royal Meteorological Society. Vol. 38. p. 291. 1912.

† Manuscript of lecture on "The Water in the Atmosphere."

‡ Taylor, "The Chemistry of Colloids," p. 18.

" phase, which is finally solid, makes its appearance suddenly,
" whether from vapour or solution, it appears first as a liquid;
" it may run through many intermediate (labile) forms before
" reaching its final solid form. Sulphur, for instance, forms
" globules, which crystallise later. Crystallisation as spherolites
" is well known."

When, then, water vapour condenses at low temperatures it forms, first of all, in liquid drops which crystallise afterwards.

56. *Snow.*—Once the first crystals are formed, further condensation takes place, but now the vapour condenses directly into the solid form without going through the intermediate liquid stage. Water crystallises in the hexagonal form. Snow flakes are formed of one or more ice crystals and the variety of patterns formed as the result of the agglomeration of the crystals is almost infinite. When snow falls with comparatively high temperatures, large, wet flakes are often the result; with lower temperatures, the flakes are smaller; and, if the temperature be much below the freezing point (32° F.) "snow dust" results, that is, the crystals are so small as to appear like dust.

57. *Sleet.*—Sleet, which is such a common phenomenon in such countries as the British Isles, may be defined as the precipitation of snow and rain together, or of partially melted snow. It is, perhaps, snow which has fallen through an inversion of temperature. The layer of comparatively warm air thus encountered causes a partial liquefaction, especially if the temperature be much over 32° F. as it often is in an inversion comparatively near the ground in temperate latitudes.

58. *Glazed Frost.*—Glazed frost is, in England, a comparatively rare phenomenom. It is important, however, inasmuch as when it occurs it greatly impedes transport, even rail locomotion being rendered difficult. In the previous section it was stated that sleet is caused by snow passing through an inversion of temperature, in which passage it is partially liquefied, the temperature experienced being over the freezing point. If however, the surface temperature is below the freezing point, the partially melted snow will re-freeze when it reaches that surface so that a layer of ice is formed on all objects on the ground exposed to the precipitation. It is this layer of ice which consitutes glazed frost.

CHAPTER X.

Weather.

59. *The Beaufort Notation.*—It is found extremely convenient to have some notation in which the weather, either prevailing at the time or which has been experienced, can be briefly but comprehensively expressed. Such a notation has a great value for use on synoptic charts, a consideration of which will be found in Part II of this book.

For use in the United Kingdom, Admiral Sir Francis Beaufort who, it will be remembered, has already been mentioned in connection with the Beaufort Scale for wind, introduced a system of notation consisting as a rule of the first letter of the phenomenon to be indicated. Various additions to his notation have been made from time to time.

The Beaufort Weather Code, however, makes no reference to several important matters such as gales or the various optical phenomena which frequently occur. Moreover, it is not international in character; and internationalism is a very desirable asset in such a study of world-wide phenomena as is meteorology. Consequently, by international agreement, a code of symbols in place of letters has been arranged. Neither the Beaufort Scale nor the International Code of Symbols is quite comprehensive and, naturally, overlapping occurs. The complete scheme of both is given for purposes of reference. (*See* Table III).

TABLE III.

The Beaufort Weather Code and the International Weather Symbols.

Beaufort Letter.	International Symbol.	——
b	...	Blue sky, cloudless, or not more than one quarter covered.
bc	...	A combination of blue sky with detached clouds.
c	...	Sky mainly cloudy, but with openings between the clouds.
o	...	Completely overcast.
g	...	Gloom.
u	...	Ugly, threatening sky.
e	...	Wet air, without rain falling.

Beaufort Letter.	International Symbol.	——
r	or ●	Continuous rain.
d	●₀	Drizzle.
s	*	Snow.
p	●	Passing showers.
h	▲	Hail.
...	△	Soft hail.
...	←	Ice crystals.
...	⊠	Snow on ground.
...	⇢	Snowdrift.
...	≈	Gale.
q		Squalls.
l	<	Lightning.
t	T	Thunder.
...	⚡	Thunderstorm.
f	≡	Fog.
fe	≡⋮	Wet fog.
m	≡°	Mist.
...	≡	Ground fog.
z	∞	Dust haze.
w	⌓	Dew.
x	⌊	Hoar frost.
...	V	Rime.
...	~	Glazed frost.
v	...	Unusual visibility of distant objects.
...	⊕	Solar halo.
...	⊙	Solar corona.
...	⊍	Lunar halo.
...	⊎	Lunar corona.
...	⌒	Rainbow.
...	⌅	Aurora.
...	⌓	Zodiacal light.

60. *The Control of Weather Changes.*—The chief factors controlling the weather of any area may be briefly summarised as follows:—

(*a*) The diurnal variation of insolation from day to night.
(*b*) The annual change of insolation from summer to winter.
(*c*) The passage of cyclonic and anti-cyclonic areas and their attendant smaller storms. (An extended consideration of these systems is given in Part II. of this book.)

61. *The General Weather of the Various Zones.*—In order to gain a broad view of weather in its general relation to latitude, it is interesting to consider very briefly the general weather experienced in the various zones into which the globe may be divided.

62. *The Torrid Zone.*—The Torrid Zone, which embraces about half of the surface of the globe and has a large oceanic area, is chiefly characterised by a regular sequence of diurnal changes, with a comparatively regular and steady change from season to season. The days are very much alike; clouds increase in the morning and decrease in the evening, and the night skies are mostly clear. Rain occurs chiefly in the afternoon when it occurs at all as, at that period, convectional up currents have reached their maximum. This regular daily routine of weather changes is seldom interrupted by cyclonic storms.

The Torrid Zone should, however, be divided into two sections; first, the "Doldrums," and second, the trade wind belts.

The weather of the "Doldrums," the region between the trade wind belts, is hot, moist and cloudy with frequent rains returning day after day with much regularity. Calms are frequent, and the wind generally does not exceed a few miles per hour in velocity. Thunderstorms of terrific violence occur from time to time. As would be expected, that part of the region which has land as the greater part of its surface has much more pronounced weather changes than does the part which is mostly sea.

The trade wind belts at sea are characterised by the constancy of the winds which blow from approximately the same direction and with the same speed both day and night. Moderate amounts of cloud occur in the daytime, but are dissipated as night approaches, and rain is not frequent. Cyclones occasionally enter these belts and control both weather and wind. The annual and diurnal ranges of temperature are small.

In the trade wind belts on land, the dryness of the air and the increase in the diurnal range of temperature compared with the belts at sea are the most remarkable features. In the hot seasons the temperature during the day may reach to a very high maximum, but the nights are cool.

The monsoon regions, especially of India, provide the greatest extremes experienced in the Torrid Zone. The weather in one season is comparatively cold and dry; that in the other warm and sultry with much rain.

63. *The Temperate Zones.*—The Temperate Zones differ from the Torrid Zones in that in them chief control of the weather is taken by the non-periodic phenomena of cyclones and anti-cyclones. Consequently, the winds and weather do not show the regularity which characterises the zone already considered. Weather is not diurnal, and the changes are more frequent and more capricious. A study of the weather and wind sequences associated with the travelling systems of cyclones and anti-cyclones, which will be given later, will reveal more clearly what these changes are.

64. *The Frigid Zones.*—It must be remembered that in very high latitudes the diurnal control of weather is completely, or almost completely, lacking. For two or three months in the depth of winter the sun does not rise above the horizon; for two or three months in the middle of summer it does not sink below it. The weather changes much as it does in the lower latitudes of the Temperate Zones according to the control of passing cyclones and anti-cyclones; and in areas, like North Russia, which are inhabited the main features of the meteorological year are the times of the thawing and freezing of the seas and rivers.

PART II.—SYNOPTIC METEOROLOGY.

CHAPTER XI.

Introductory.

65. *General.*—Modern meteorology must be regarded as the work of an organisation and not of any individual. One of the chief duties of a Meteorological Office now-a-days is the making of forecasts of weather, and this involves the co-operation of hundreds of people. The making of synoptic charts is an essential part of the process of forecasting. By a synoptic chart is understood a map of the geographical area under consideration showing the distribution of the various meteorological elements such as wind, pressure, temperature and the like over that region for a given point of time. Such maps are usually prepared four times daily for fixed hours of observation, which, in the British Isles, are 1 o'clock and 7 o'clock in the morning, and 1 o'clock and 6 o'clock in the afternoon, times being Greenwich Mean Time. Their preparation connotes a corps of observers and a well arranged distribution of meteorological stations. It is the duty of such stations to take, at the

prescribed hours, careful observation of the meteorological elements required and to transmit the results of their observations to the Central Office, to reach that Office as soon as possible.

The speed of transmission of these messages is obviously very important. The synoptic charts have to be prepared, and the forecasts of coming weather based upon them have to be issued as soon as possible, for speed in issuing forecasts is a most commendable meteorological virtue, inasmuch as weather changes in such a region as the British Isles occur, sometimes, very rapidly, and these changes, as in the case of gales, may involve much damage and even loss of life. Forecasts issued promptly may often enable the authorities concerned to take such precautions as may minimise both the damage to property and the danger to life.

Here, then, in the question of speed of transmission enters a third factor; the factor of adequate and rapid means of communication between the observers and the Central Office, where the maps are prepared and the forecasts issued. Ordinary telegraphy, wireless telegraphy, and the telephone have done much to secure the efficiency of modern forecasting. Each link in the chain is very important; the observers at the outlying places of observation must be thoroughly competent, the means of communication they have with the Central Office must be rapid and exact, which is a matter of thoroughly competent telegraphists, and the forecaster drawing the charts and forecasting from them must also be thoroughly competent.

But it cannot be too much emphasised that even an expert meteorologist is not able to do much in the way of good forecasting if he has no current synoptic chart. No amount of knowledge of weather saws and maxims is of much avail. Even a thorough knowledge of cloud forms is not sufficient, and the "weather glass" with the legends around its dial is a snare and a delusion. Synoptic charts, properly interpreted, are the essential matter in sound forecasting; and the interpretation involves much appeal both to physics and to precedent.

CHAPTER XII.

Pressure and its Measurement.

66. *The Pressure of the Atmosphere.*—Perhaps the most important meteorological element entered upon synoptic charts is the pressure of the atmosphere as determined at the various meteorological stations contributing to the preparation of those charts.

Pressure is the most important of the meteorological elements because all the other elements—wind, humidity, and the rest—seem to depend upon it, or, rather, upon its changes. The characteristic of fluid pressure which must be borne in mind—

and air is a fluid—is that of transmission. If water be considered that water will flow through any crevice, no matter how small, in order "to find its own level." The same is true of air, except that air does not take so long. In any room there are some crevices and through these crevices the air will flow in the endeavour to settle down in equilibrium, and such equilibrium is attained very rapidly. Therefore, the atmosphere is regarded as having the same pressure at the same levels so long as the air is not moving; and movement of the air is regarded as a component in the equalising process.

67. *The Measurement of Pressure.*—The pressure of the atmosphere is measured by means of barometers, and barometers are of two kinds; first, those in which the pressure is balanced by the weight of a column of liquid, and second, those in which movements of the flexible lid of a box which is nearly exhausted of air are recorded.

The barometers in which a column of liquid is the main feature will be considered first. The making of a simple barometer of this type is an easy matter. A glass tube, about 33 inches long and closed at one end, is taken and completely filled with mercury. It is next inverted with a finger pressed tightly against its open end. The next step is to immerse the finger, and the end it is closing, under the surface of mercury contained in a bowl. The tube is brought into the vertical position and the finger withdrawn. On withdrawing the finger the mercury drops. When things have become steady it is found that a column of mercury, about 30 inches in height above the level of the mercury in the bowl is still maintained in position in the tube. It is so supported by the pressure of the air acting downwards on the surface of the mercury in the bowl. The space above the mercury in the tube is a vacumn, that is, it is practically entirely free from air, and is termed the "Toricellian vacuum" after Torricelli, the Italian, who first performed the experiment which has been described in 1643. Repetitions of the above experiment performed in rapid succession on the same day may show no difference in the height of mercury supported. A daily experiment done for several days in succession, however, will reveal that the height supported varies appreciably from day to day.

The experiment could be repeated using other liquids than mercury. Water, for example, could be used but as mercury is, approximately, $13\frac{1}{2}$ times as heavy as water, it is clear that, if the atmosphere supports about 30 inches of mercury, it would support about 405 inches of water, or nearly 34 feet, which would make the length of tube required extremely long and cumbersome in working. Nearly all liquids suffer from the same practical disadvantage and mercury, on account of its high density, remains clearly marked out as the most suitable liquid for barometric purposes. Moreover, its opacity makes it peculiarly easy to read. A great additional advantage is that

its vapour has a very low pressure at ordinary temperatures and this makes possible the existence of a nearly perfect vacuum above it.

The standard mercurial barometers, such as the Fortin pattern and the Kew pattern, used in metereological stations, are made on the same principle as the simple barometer whose construction has already been described. For details of the refinements introduced to obtain a high degree of accuracy in the Fortin and Kew patterns the student is referred to "The Observer's Handbook," issued by the Meteorological Office, Air Ministry, London, and published by His Majesty's Stationery Office.

68. *Corrections to be applied to Barometer Readings.*—The height of the mercury as read needs to be corrected for—

(*a*) The temperature of the instrument;
(*b*) The latitude of the place where the instrument is set up;
(*c*) The height of the cistern of the instrument above sea level.

These corrections are necessary in order that the pressures when plotted on the synoptic charts shall be strictly comparable.

The correction for the temperature of the instrument is due to the errors introduced by the expansion and contraction of both the mercury and the metal scales. If two barometers were placed at exactly the same level, one in the warm air of a room, the other in the colder air outside in the open, the one in the warm room would read the higher, but the actual pressure exerted by the atmosphere as the levels are equal would be the same. The correction is carried out and strict comparison is secured by reducing all readings to what they would be if the temperature of the instrument were some fixed temperature. This fixed temperature is taken to be 32 F°.

The curvature of the earth is not perfect and the force of gravity varies according to latitude, reaching a maximum at the poles and a minimum at the equator. Thus, if there were uniform atmospheric pressure over the whole globe, a mercurial barometer at the equator would read higher than one at either pole. To avoid errors due to this variation of gravity with latitude all barometric readings are corrected to what they would be if the instrument were in some standard latitude, which latitude is taken to be 45°.

The correction for height above sea level is clearly necessary if readings all over an area are to be comparable in view of the fact that pressure decreases with height. What is needed in synoptic charts is a knowledge of the changes of pressure due to general causes and not to such ones as are due to local configuration. This error is avoided by correcting the readings to what they would have been if situated at a standard height. The standard height selected is that of mean sea level, which differs slightly from country to country, but in the British Isles

is an arbitrary level at Liverpool. The differences of the level taken as sea level in different countries are not great enough seriously to vitiate the use of the readings from those various countries as comparable upon synoptic charts.

The barometric pressures, then, appearing on the synoptic charts are those which would have been read if all the barometers supplying readings were at a temperature of 32° F., at a height equal to mean sea level, and situated in latitude 45° N. or S.

69. *Barometric Units.*—The purpose of the barometer is to give the value of the pressure of the air. Owing to the convenience of the mercury barometer, it became the custom to express the pressure in terms of the height of the column of mercury, inches being used in England and millimetres on the continent of Europe. If a water barometer had been in general use, the value would no doubt have been expressed in feet or metres of water. In an aneroid barometer neither inches of mercury nor feet of water are intrinsically suitable, but nevertheless inches of mercury formed the standard in this country.

Pressure is, however, not a length but a force per unit area, and it is usually expressed in this way except in the particular case of the pressure of the atmosphere. For example, the pressure in a steam engine is expressed in lbs. per square inch.

By a fortunate coincidence the pressure of the atmosphere near the earth's surface is very nearly one million times the fundamental unit of pressure in the metric system, that is, 1 dyne per square centimetre, and it is therefore not merely of scientific value but also of practical convenience to use this system. The millibar is 1,000 of these fundamental units and the pressure of the atmosphere near the earth's surface is approximately 1,000 millibars. The millibar is a conveniently sized unit and mercury barometer can be graduated in such a way that the pressure in millibars is read off with great ease.

The derivation of the millibar is now given more completely.

The unit of force on the C. G. S. (centimetre-gramme-second) system, now used universally for most scientific work, is the force which produces an acceleration of 1 centimetre per second in a mass of 1 gramme, and is termed a dyne.

The unit of pressure in the C. G. S. system, as already stated, is 1 dyne per square centimetre.

The dyne is, however, a very small unit and so a mega-dyne, that is, one million dynes, called a bar, is adopted as the practical unit of force, and this leads to the use of the millibar.—

1 bar is equal to the pressure of 1 mega-dyne per square centimetre, that is, to 1,000,000 dynes per square centimetre; 1 millibar = $\frac{1}{1000}$ of a bar and is therefore equal to the pressure of 1,000 dynes per square centimetre.

1,000 millibars, that is, 1 bar, are equivalent to the pressure of a column of mercury 29·531 inches (750·1 millimetres) high at a temperature of 32° F. (0° C) under the conditions of gravitation existing in latitude 45° N. or S.

In Table IV. will be found values facilitating conversion from one system of barometric units to another. The values refer to standard conditions of temperature and latitude.

TABLE IV.

Conversion Table for Pressure.

Inch.	Millimetre.	Millibars.
1	25·4	33·9
0·0394	1	1·33
0·0295	0·75	1

The principal advantage of using the millibar as a unit is that a pressure quoted as a number of millibars is completely definite; millibars can be used just for pressure and for nothing else.

As the reading of a barometer is not independent of either the temperature of the instrument or of the latitude of the place where it is set up, it follows that the 1,000 millibar graduation can only be correct for one particular temperature at each latitude. The temperature appropriate to latitude 45° is termed "the standard temperature" of the barometer. The temperature at which the 1,000 millibar graduation reads correctly in any other latitude is termed "the fiducial temperature" for that latitude. Both the "standard" and the "fiducial" temperatures refer to sea level, and it should be noted that the "standard" temperature in latitude 45° is also the "fiducial" temperature for sea level in latitude 45°.

It needs to be recognised, however, that the conditions of temperature and latitude which ensure that the 1,000 millibar graduation is correct are not necessarily such as make graduations in other parts of the scale correct. The "standard" temperatures applicable to latitude 45° for several readings of the scale are usually supplied with a good barometer graduated in this system, and from these "standard" temperatures the corresponding "fiducial" temperatures for the various readings of the scale given can be computed.

In any particular case, then, the barometer graduated in the millibar system is read as well as the thermometer attached to the instrument giving the temperature of that instrument. The "fiducial" temperature for that part of the scale where the mercury level stands is then read from previously computed tables. The difference between this "fiducial" temperature

and the attached thermometer reading is noted and the correction to be added or subtracted to correct the reading down for temperature is read from prepared tables. The remaining correction is for height above sea level. Once again this is done by reference to tables and here it is the temperature of the outside air which counts.

For a fuller explanation of the methods of correction by "fiducial" temperatures and for the necessary formulæ and tables used in that correction, the reader is referred to the "Observer's Handbook" issued by the Meteorological Office, Air Ministry, London.

70. *Aneroid Barometers.*—The second type of barometer in general use is that in which the compression or recovery of a box which is nearly exhausted of air and has a flexible lid is recorded. Such barometers are termed aneroids. An aneroid consists generally of a circular metallic chamber hermetically sealed which has been rendered practically vacuous. The lid is made of very thin elastic metal, and by an arrangement of levers and springs the movements of this elastic lid are recorded by a needle moving over a dial.

The pressure within the box is very small, whilst the lid is carrying the weight of the outside air upon it. Any increase in outside pressure pushes in the lid slightly and any decrease allows the lid to recover. If the dial be properly calibrated the needle recording the movements of the lid gives the pressure of the outside air.

Aneroids do not require correction for latitude or temperature, but only for height above sea level and for index error. Whilst extremely suitable for explorers and for mountaineers on account of their portability and comparative lack of fragility as compared with mercurial barometers, aneroids are not accepted as being sufficiently accurate for use at meteorological stations as their mechanism introduces errors beyond the limits allowed.

Aneroids are very useful in the rapid determination of heights. As a rough rule it may be said that the barometer falls 30 millibars per 1,000 feet of elevation for low altitudes. Starting, then, with a normal pressure at sea level and marking that as 0 feet, the dial of the aneroid may be calibrated in heights instead of pressures. Arrangements can be made to enable the zero height mark to be adjusted to the actual pressure existing at any place, so that heights above that place can be read off to a fair degree of accuracy directly from the dial.

71. *Barographs.* — The ordinary barograph is really an aneroid barometer fitted with a lever recording on a chart or a drum, the drum being kept revolving by clockwork. By using such an instrument a continuous record of the pressure from moment to moment is obtained. The great use of a barograph is to show how the pressure is varying. It must be standardised

daily by comparison with readings given by a mercury barometer.

72. *The Diurnal Variation of the Barometer.*—An examination of barograph traces taken in quiet weather over a long period reveals one striking fact, and that is a definite diurnal variation of pressure. There is a slight rise of pressure between about 4 o'clock in the morning and 10 o'clock in the morning, and also between about 4 o'clock in the afternoon and 10 o'clock in the afternoon, with corresponding falls in between. This diurnal variation is most marked in the Torrid Zone and becomes less distinct with increasing latitude. This would be expected as the cause of the diurnal pressure variation is to be found in the diurnal variation of temperature. Fig. 6 shows the variation in diagrammatic form. The variations in the figure are exaggerated.

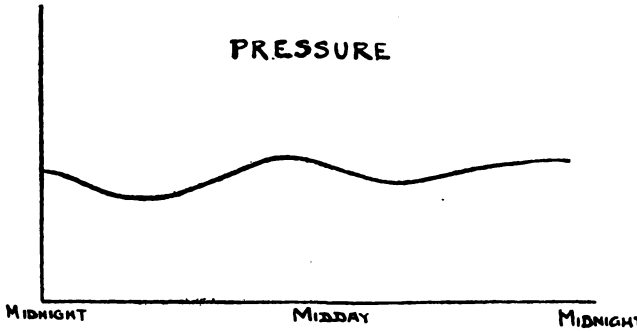


FIG. 6.—DIURNAL VARIATION OF PRESSURE.

CHAPTER XIII.

The Making of Synoptic Charts and some Lessons derived from them.

73. *The Foundations of a Synoptic Chart.*—The forecaster receives from several stations distributed over the region for which he is concerned observations taken at precisely the same hour. These observations include the wind direction and also its force estimated on the Beaufort Scale (*see* section 5), the temperature of the dry-bulb thermometer, the pressure corrected down to 32° F., and to sea level in latitude 45°, the weather and other special data. He sets the details down beside the location of the particular station on a blank map, showing the wind direction by an arrow with its point actually on the spot marking the station and with feathers equal in number to the Beaufort Scale figure indicating the force, calms being indicated thus:—0. The arrows are drawn so as to be travelling in the wind. The pressure is added in plain figures as is the temperature, whilst the weather existing at the time is either denoted

DISTRIBUTION OF WEATHER, 6 P.M. 2nd AUGUST, 1918.

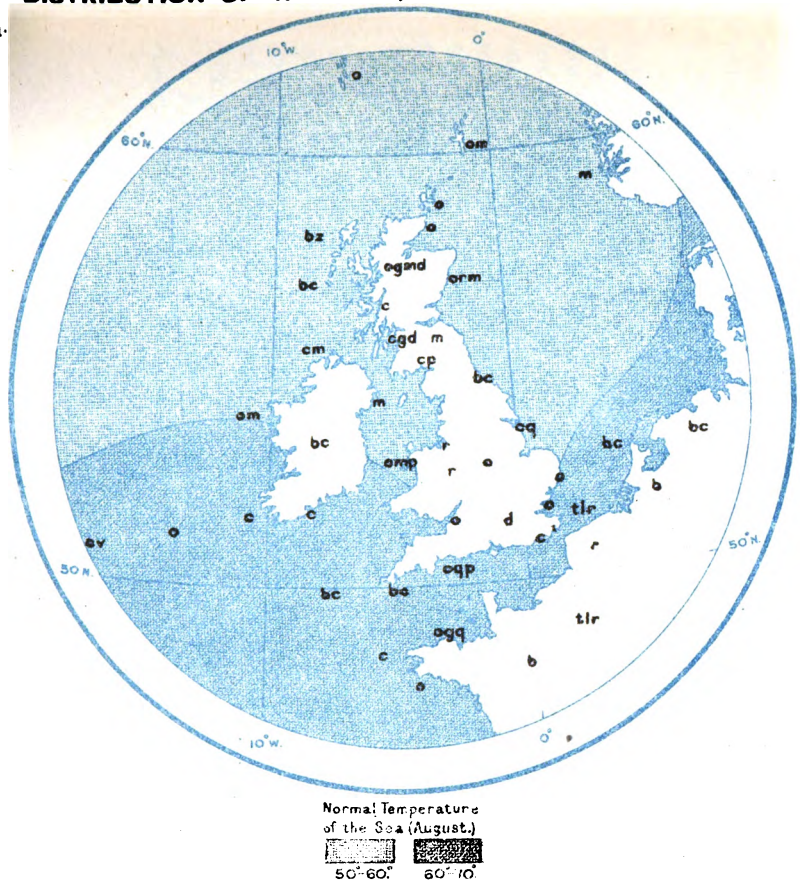
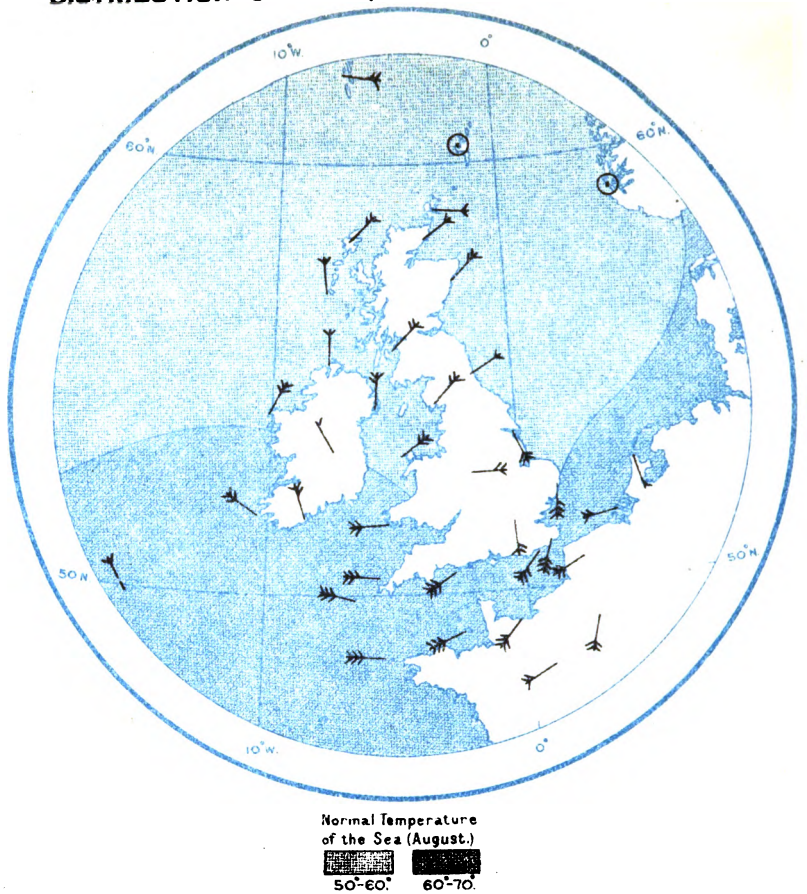


Fig. 7.

DISTRIBUTION OF WIND, 6 P.M. 2nd AUGUST, 1918.



⊙ Calm.
force 1.
force 3
force 4.

Fig. 8.

H.M.S.O. Press, Kingsway, W.C.2,

S.O.P. Pe. 18585/432. W.6438. D.6216. 3000 11/21.

by the letters of the Beaufort Notation of Weather (*see* section 59) or by a conventional picture code. Whether the pressure at the place is rising or falling or steady as denoted by the barograph there is denoted by means of a conventional sign (*see* Table V.), and the amount that the barograph has varied within the three hours preceding the hour of observation is added, also in a conventional code, generally by a figure showing the number of half-millibars of change.

TABLE V.

Conventional Signs to illustrate Barograph behaviour.

Barograph behaviour.		Conventional Sign.	Code Figure.
Steady or rising	The barometer is now higher than, or the same as, three hours ago.	O or +	0
Rising, then steady		+ O	1
Rising, then falling		+ −	2
Falling or steady, then rising		− + or O +	3
Unsteady, but rising		U +	4
Falling	The barometer is now lower than three hours ago.	−	5
Falling, then steady		− O	6
Falling, then rising		− +	7
Steady or rising, then falling		O − or + −	8
Unsteady but falling		U −	9

The actual change in the pressure at the station within the past 3 hours is termed the "barometric tendency" and, as has already been stated, is usually given in the United Kingdom in half millibars. The conventional sign indicating the type of variation is termed the "characteristic" of the tendency. The code figures used in practice to report the variation depend, it will be noticed, on the position of the pen on the chart with regard to its position 3 hours before.

74. *Isobars.*—The most important thing on a synoptic chart is the pictorial representation of pressure distribution at sea level which is secured by drawing what are termed isobars. Isobars are lines drawn through places at which the pressures corrected for temperature and latitude and reduced to sea level are the same. The isobars are usually drawn for definite pressures with fixed intervals of pressure between them. As it is generally the case that no stations supplying observations actually have these definite pressures, the isobars are drawn by a process of interpolation.

Figures 7, 8, 9, and 10 should now be carefully studied. They all refer to the conditions over the British Isles at 6 p.m. on the 2nd of August, 1915, and they serve to illustrate the making of a synoptic chart. Figure 7 illustrates the distribution of weather, the Beaufort Scale of Weather Notation (*see* section 59) being used.

Figure 8 gives the distribution of wind. Figure 9 shows the distribution of pressure and the isobars are drawn in; the

isobars drawn are those for 1,000 millibars, 1,005 millibars and so on at intervals of 5 millibars, and the interpolation involved should be carefully noticed. Figure 10 gives a chart combining all the foregoing particulars, but the weather is now expressed pictorially instead of in the Beaufort Notation, and the area considered is somewhat larger and more isobars become necessary.

Isobars are almost exactly analogous to the contour lines appearing on an ordinary geographical map; but whereas contour lines apply to heights, isobars apply to pressures.

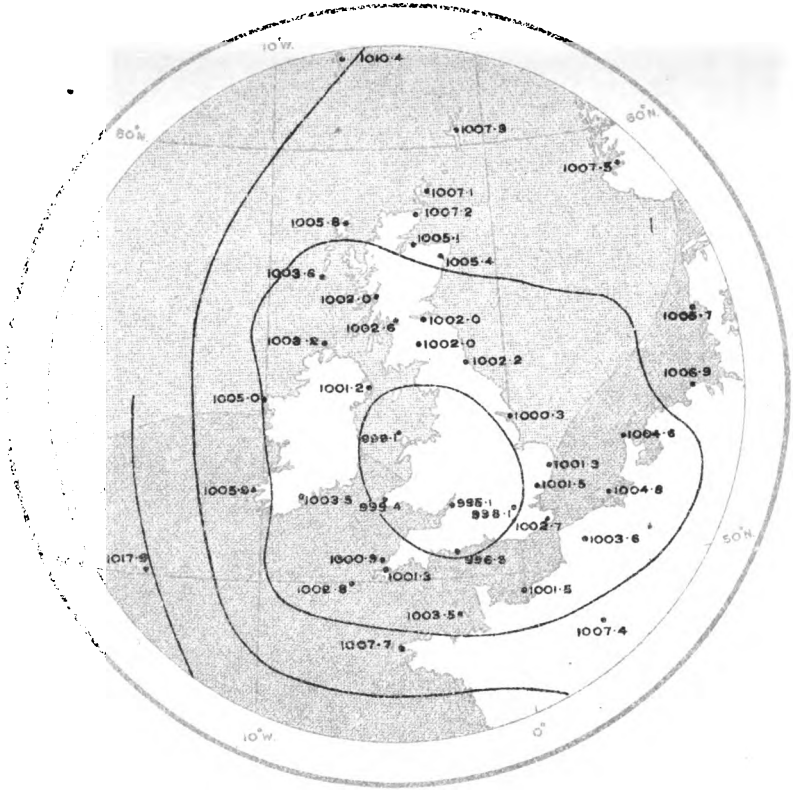
75. *Buys Ballot's Law.*—A study of synoptic charts caused Professor Buys Ballot of Utrecht to enunciate in 1857 the famous law which bears his name. Buys Ballot's law is as follows:— If, in the northern hemisphere, you stand with your back to the wind, pressure is lower on your left hand than on your right. In the southern hemisphere the reverse is true for there, if you stand with your back to the wind, pressure is lower on your right hand than on your left.

The student should demonstrate the truth of this law to himself by reference to as many synoptic charts as possible, including the one shown in Figure 10.

A further point to be noticed is, that the winds seem closely to follow the lie of the isobars but shows, generally, a tendency to turn inwards towards the low pressnre. This deviation from the true lie of the isobars is generally between 0° and 45°, but is sometimes greater. The attention paid by the wind direction to the isobar direction is greatest in polar regions. As the equator is approached the attention paid is less; it is, however, still quite noticeable at 20° N. or S. latitude. Nearer the equator still the attention paid is very little and, actually, at the equator itself is non-existent. Crossing the equator means that the directions of the wind with regard to pressure are exactly reversed in accordance with Buys Ballot's Law. The change over is not noticeable, however, in practice owing to the fact that the equatorial regions constitute a belt of low pressure, the Doldrums, in which only light and variable winds blow as a rule and in which calms are frequent.

76. *The Strength of the Wind.*—Another lesson to be derived from a consideration of a collection of synoptic charts relates to the strength of the wind. Hardly any map will fail to reveal to the observant student that where the isobars lie close together the wind is strong, and, where far apart, weak. This is quite what would be expected, remembering the analogy between isobars and contour lines. On a geographical map, contour lines close together indicate steep gradients or slopes down which it may be imagined that, if a stream existed, the water would rush tumultuously; contour lines far apart, on the other hand, indicate gentle gradients or slopes down which the water in the stream would flow slowly. What applies to

DISTRIBUTION OF PRESSURE, 6 P.M. 2nd AUGUST, 1915.



Normal temperature of the sea surface

The figures give the sea-level pressures in millibars.
The black lines are isobars.

Fig. 9.

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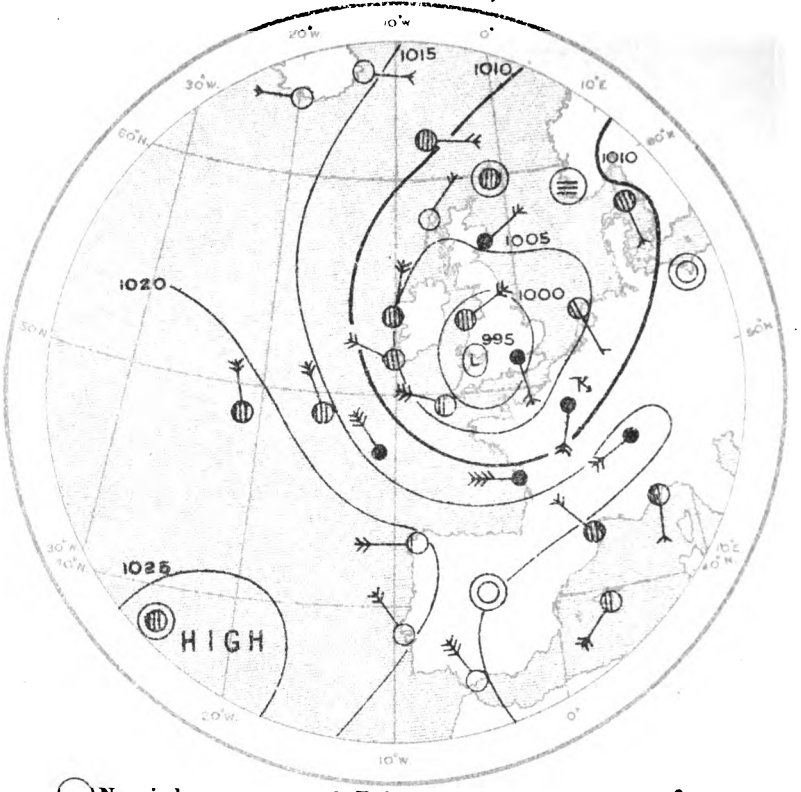
DISTRIBUTION OF WEATHER, WIND, AND PRESSURE, 6 P.M. 2nd AUGUST, 1915.



No wind.
Clear sky.
Half clouded.
Overcast

Rain.
One quarter clouded.
Three quarters clouded
Thunderstorm.

Mist.
Fog.

Fig. 10.

S.O.R.P.9. /8585/432. wt.6498. D.62/6. 3000. 11/21

contour lines applies to isobars. Isobars close together, that is, steep pressure gradients, mean that the air flow is rapid, that is, that winds are strong; isobars far apart, that is, slack pressure gradients, mean that the air flow is gentle, that is, that winds are light. Isobars very far apart mean that the air flow is inappreciable, and calms result.

77. *The Gradient Wind.*—It will be seen then, that it should be possible to calculate the wind speed at any place from the pressure gradient at that place as shown by a carefully drawn synoptic chart. This can be done and the result obtained is termed the gradient wind. In practice, however, the wind existing at the surface is found to be, as a rule, less than the calculated gradient wind. This is due to the friction of the surface of the earth; the calculated gradient wind agrees with, in most cases, the actual wind met at about 1,500 feet above the surface.

CHAPTER XIV.

Types of Pressure Distribution.

78. *Introductory.*—Many thousands of synoptic charts of the British Isles have been prepared for various hours, but no two charts have ever been found to be identical; and what applies to the British Isles applies to any other region. Similar the charts may be with regard to some features, but that is all. The variety of distribution is endless.

But emerging from the many variations, seven main types* of isobaric distribution may be recognised. Those seven types are as follow:—

(*a*) Depression or low;
(*b*) Anti-cyclone or high;
(*c*) Col;
(*d*) Secondary depression;
(*e*) V-shaped depression;
(*f*) Wedge of high pressure;
(*g*) Straight isobars.

The main features of each of these types will now be considered.

79. *Depressions.*—Depressions are parts of the atmosphere where the pressure is low. They appear on synoptic charts

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* For a classification of pressure distribution into 28 types, the student is referred to "Aids to Forecasting" (Geophysical Memoirs, No. 16), by E. Gold, F.R.S., issued by the Meteorological Office, Air Ministry, London, 1920. This is the best extended classification of types of pressure distribution known to the present author.

as series of closed isobars, approximately oval or circular in shape, with the minimum pressures occurring in the centres. An example of a depression, with its centre marked L, is shown in Fig. 10.

The sizes of depressions vary enormously. One example may have a diameter of 1,000 miles or more ; another, a diameter of much less ; others, too, which constitute the tornadoes of the United States of America or the typhoons of the China Sea, have very small diameters, indeed, sometimes under 10 miles. A depression in which the barometer is very much lower in the centre than it is on the margins is said to be deep ; one in which there is comparatively little difference of pressure between the centre and the margins is said to be shallow.

Alternative names for a depression are " low " and " cyclone." The use of the term " low " has now become popular and little can be said against it ; but care needs to be exercised in using the term " cyclone." In America, especially in newspaper reports, the term " cyclone " is applied to what is more properly called a " tornado," that is, a depression of extremely small diameter which is accompanied by exceptionally steep pressure gradients, and, consequently, by exceptionally violent winds which cause great damage. In the British Isles, the connotation of " cyclone " is that of a large area of low pressure accompanied by broad sheets of cloud, comparatively large areas of rain and winds which may, or may not, be violent. The two uses of the term " cyclone " need to be carefully differentiated. The English use is distinctly the more generally accepted scientific one, and even American meteorologists, as apart from the American general public, so use it, calling their smaller whirling storms by the correct name of " tornadoes." Any use of the word " cyclone " in this book must be taken as having the scientific connotation.

The winds in a depression obey Buys Ballot's Law (*see* section 75). One very convenient way of stating the relation of wind direction to depressions is to say that winds blow in an anti-clockwise direction around the centre of low pressure. The winds, too, generally exhibit quite markedly the tendency to turn inwards towards the low centre ; and their force depends upon the steepness of the pressure gradient, that is, upon the distance apart of the isobars.

80. *The Nomenclature of a Depression.*—There is a very definite nomenclature, due to Abercromby, attaching to depressions. As the terms employed will be frequently used in what follows, a diagram (Fig. 11) is given illustrating these terms. Reference is made more fully in section 82 to the travel of depressions, and hence the " path " marked in the figure. The " trough " marks the period of lowest barometer during the passage of a depression over a place.

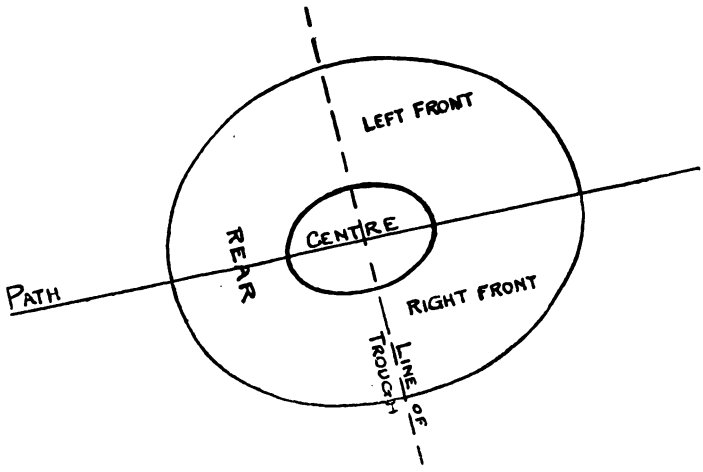
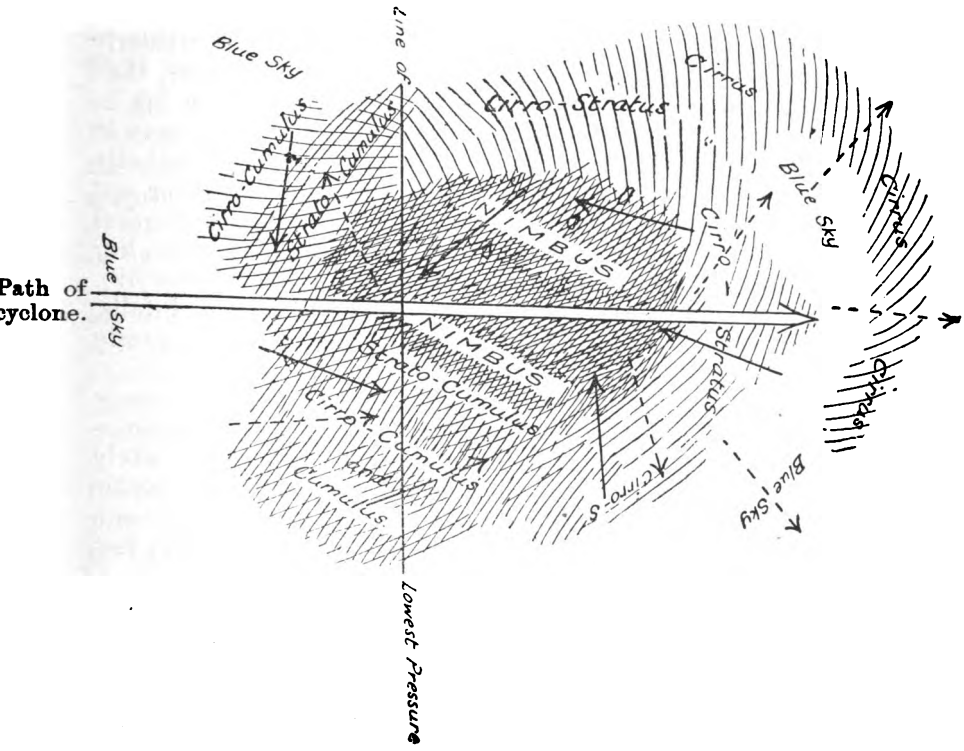


FIG. 11.—NOMENCLATURE OF A DEPRESSION.



——→ Wind direction at the earth's surface.

- - - - → Wind direction in the region of the cirrus cloud.

FIG. 12.—DISTRIBUTION OF A CLOUD IN A DEPRESSION.

81. *The Weather in a Depression.*—An examination of the weather occurring in several examples of depressions as seen on

synoptic charts reveals the fact that there seems to be a fairly definite distribution of cloud and rainfall connected with them.

The distribution of cloud is shown in Fig. 12, which figure also shows the wind direction both at the earth's surface and at the height of the cirrus clouds. It will be noticed that the whole depression is ringed around with clouds of the cirrus types which are especially prominent in the extreme front of the system. It will be noticed, too, that the cloud lowers from the margins towards the centre, and that the area approximately surrounding the centre is covered with nimbus clouds. This area of nimbus cloud is generally the scene of fairly continuous rain.

It should be noted, however, that the distribution of rainfall within a depression presents more difficulty in the way of general statement than does the distribution of cloud. Each depression seems to have its own peculiarities of rainfall. Generally, in fact, the rain seems more marked in the left front near the centre than elsewhere. This is to be explained in the following way: The left front of the depression is a region of easterly winds; the right front, of southerly or south-westerly winds. The easterly winds are colder, and hence denser, than the southerly or south-westerly ones, which, however, so far as the British Isles are concerned, differ from the easterly ones in being saturated or nearly so. This means that the southerly and south-westerly winds are forced to rise over the colder and denser easterly ones, and the ascent is accompanied by dynamical cooling and, as the rising air is of high relative humidity already, much low cloud formation and rain (*see* section 49). The rain is carried on in the wind a little further and falls, mainly in or near the left front, through the surface easterly currents.

It should be clearly recognised that the statements already made about the distribution of weather in cyclonic systems can only be taken as average statements and not as definitely applicable to any given depression appearing on a synoptic chart. The depressions, however, which do not approximate fairly closely to those general statements are, comparatively, few in number.

82. *The Travel of Depressions.*—An examination of synoptic maps for a succession of days reveals the fact that depressions are not stationary, but travel. Generally speaking, considering their centres, they travel from a westerly point to an easterly one, with a tendency towards north, so that a large number move from south-westerly to north-easterly.

The result of researches, however, especially for North-West Europe, gives the very disappointing result which has been expressed* as follows:—"No path can be drawn so

* "Forecasting Weather." Sir Napier Shaw, F.R.S. (Messrs. Constable and Co., Ltd.). Chapter XV.

" tortuous and so out of the way that we can fairly say it must " be ruled out as a possible path for the centre of a cyclonic " depression."

Clearly the direction of travel of a depression is a matter of great importance to the weather of any particular region, inasmuch, as has been shown in section 81, definite weather is generally associated with the various parts of the system. The wind, too, varies in the different positions with regard to the centre of low pressure. A change of even a few degrees in the direction of travel of a depression moving towards the particular region under consideration may cause the wind and the weather in that region to be entirely different from what would have been anticipated if the depression had kept on its expected path.

The forecaster, then, confronted by a depression coming towards the area with which he is concerned, has to predict, as exactly as he possibly can, the course that that depression will take, for everything will depend upon that. It is of little avail to rely upon the average of the behaviour of past depressions: he must deal with the one actually advancing and deal with it as an individual possessing its own characteristics.

83. *To determine the Direction of Travel of any Particular Depression.*—Without doubt, depressions are the main factor in the weather of such a region as North-West Europe. Consequently given one upon, or one affecting, the current synoptic chart, it is the forecaster's first duty to predict the direction of its further travel.

The first step to accomplish this end is for him to acquaint himself with the past history of the depression so far as he is able so to do from a study of the three or four synoptic charts immediately preceding the actually current one. If the depression has maintained one steady course it will need strong reasons if he predict a change in that course.

He next, in English practice, considers the barometric tendencies, that is, the changes in the pressures within the three hours immediately preceding the fixed hour of observation at the various stations contributing to the synoptic chart. He then assumes, in default of strong suspicion to the contrary, that the depression will travel towards the place of greatest fall. The objection to be urged against this method is, that the tendencies are past history and that it does not follow that, because the barometer has fallen considerably at a place within the past three hours, it will continue to fall considerably there within the ensuing three hours. In practice, however, the method of predicting travel towards the places where greatest barometric falls have occurred is found to be fairly successful.

Dr. Ekholm, of Stockholm, 15 or 20 years ago, advocated the use of a new aid to the prediction of the advance of depressions. He draws charts in which it is the pressure differences from the last observation which are plotted, and not the actual

pressures observed at the time. Thus, lines of equal pressure difference, called isallobars, are obtained. Examination of successive isallobaric charts reveals that the groups of isallobars travel similarly to the groups of isobars; and Ekholm maintains that the isallobaric systems travel more regularly than do the isobaric ones. The British Isles suffer in using Ekholm's method because of their extreme western position; before the isallobaric groups are well defined, they have travelled past. Isallobaric charts are, however, useful aids in determining where the greatest barometric falls are likely to occur.

But a more useful aid in practice is to be found in a study of the wind directions at the various stations. By Buys Ballot's Law it is recognised that when the wind direction is changing, the distribution of pressure is changing also. A change of force alone, without any change in direction, just means that the isobars are maintaining their general lie unaltered, but are either crowding more together or becoming wider apart. A change of direction means that the relative distribution of the high and low pressures is changing. The "backing" of a wind, that is, its changing in an anti-clockwise direction, is a sign of the coming of a depression. That this is so is evident from the consideration that one depression follows another depression with a greater or less interval in between. By Buys Ballot's Law, the winds in the rear of the depression which has passed are north-westerly; those in front of the depression which is approaching are south-easterly. A station, then, in the line of advance of the coming depression often reveals the coming of that depression by a backing of its wind long before the centre appears on the chart; and it is a fair assumption to say that the coming depression will advance more or less directly towards the station or stations showing the backing. The importance of the meteorological observations taken at Valencia, Blacksod Point, and Malin Head, on the western coast of Ireland, can hardly be over-estimated in this respect with regard to depressions from the Atlantic Ocean advancing on to the British Isles.

Wind study is necessary for yet another method of anticipating the approach, and predicting the line of advance, of depressions, which method is due to M. Gabriel Guilbert.* An examination of synoptic charts reveals the fact that the wind forces at the various stations are often not in accord with what would be expected from the pressure gradients at those stations as shown by the charts, and that sometimes the wind directions differ also from what they should be considering the lie of the isobars. So far as direction is concerned, Guilbert considers that the wind is an abnormal one if it deviates more than 40° from the run of the isobar. He treats these abnormalities of force or direction as significant, and has formulated a set of

* "Nouvelle Méthode de Prévision du Temps," par Gabriel Guilbert. (Gaultier Villars, 1909.)

empirical rules in which he employs them as means to predict the progress of isobaric groups. It is obvious that the method implies that the wind exposures of the stations considered are perfect. This is so seldom the case and abnormalities of wind are produced so often at many stations because of some unavoidable imperfection or another of exposure that the method needs using with the utmost care.

A selection of Guilbert's empirical rules is now given :—

(*a*) A depression with winds above normal force (as compared with the pressure gradient) on all sides will fill up ; one with winds below normal force will become deeper, and, hence, depressions which are, apparently, weak will change into cyclonic storms.

(*b*) These parts of the depression in which the winds are below normal force, as shown by the pressure gradient, indicate the direction in which the depression will move ; thus, when a depression consists partly of winds that are above normal and partly of winds that are below normal, it will move in the direction of least resistance, that is, in the direction where the winds are below normal.

(*c*) Pressure increases from right to left across the line of winds too strong for the gradient. In other words, a wind above normal transfers pressure from the right to the left.

(*d*) Depressions are attracted towards the regions of least resistance ; towards regions of light airs or calms, and, above all, of divergent winds (divergent, if blowing in opposition to the normal direction corresponding to the run of the isobars).

(*e*) The existence of several anemalies in the directions and forces of winds at various stations in a limited area at the same time decides the sudden formation of an important depression over that area.

It must be confessed, however, that, whilst in Guilbert's own hands his method has given some astonishingly successful forecasts, other forecasters have found it difficult to use with much success. As has been already said, it needs to be used with extreme care, and with a real knowledge of the wind exposures of the stations where the abnormalities are occurring.

To sum up, it cannot be said that the line of advance of a depression can yet be predicted with certainty ; but a forecaster, diligent in watching the various points already mentioned, and diligent also in appealing to experience, can be very successful.

It is interesting to notice that the centres of depressions appear to have particular likes and dislikes, and these are useful, sometimes, in predicting their courses. They seem, for example, to prefer to travel over water in preference to land.

Quite often, a depression in North West Europe travels down the North Sea. This particular track is responsible for bringing Eastern England very disagreeable weather in winter, snow and sleet abounding with squalls in the north-westerly or northerly winds in the rear of the cyclonic centre. The Bristol Channel, too, is a very favourite depression track. Another peculiarity is, that on land, depression centres seem to prefer to keep to the low land, if possible.

84. *The Rate of Advance of Depressions.*—Depressions advance at very variable speeds. Across the British Isles, a speed of 20 to 30 miles per hour is very usual: sometimes, however, this speed is considerably exceeded, and sometimes depressions stay quite stationary for appreciable periods.

85. *The Sequence of Wind and Weather in a Depression.*—It is clear that the sequence of wind and weather experienced by a particular observer at a particular place as a depression passes across him depends entirely upon how he is situated with regard to the path of advance of the centre.

If he be actually on the track of the advancing centre, he will notice that the barometer begins to fall, that high cirrus cloud appears in the sky, and that the wind becomes light southerly. If it be in winter, the temperature will be above the seasonal normal. Soon the sky becomes overcast with cirro-stratus and cirro-nebula, and halos are probably seen around the sun or moon as the case may be. The wind, too, freshens. As the centre approaches, the clouds lower to alto-cumulus or alto-stratus, then to cumulo-stratus, and, finally, to nimbus when rain begins to fall. As the centre passes the rain gets heavier and the wind stronger. Next, the barometer begins to rise after the actual passage of the trough line, and gusts or squalls of wind are experienced. The wind changes to north-west or north, and, often, blows more strongly than before. As the centre moves away the rain ceases, or only occurs in showers, the cloud shows signs of breaking, and long rolls of strato-cumulus appear with patches of blue sky. Soon, the showers, stop altogether, the barometer rises rapidly, the cloud gets higher, some cirrus appears and the wind, whilst still remaining north-westerly, moderates. Very soon, now, the depression entirely passes out of range and blue sky, with light winds, prevails.

If the observer be situated to the south of the track of the centre, instead of actually upon the track of the centre, he will experience much the same sequence of cloud and rain as has been described, but the winds will show a continual veering from south-east to west as the centre passes north of him, and to north-west as it passes away. If he be to the north of the centre's track, the wind will back from south-easterly at the commencement, through east as the centre passes actually due south of him, and, finally, to north-easterly and northerly as it passes away.

The time occupied in this cycle of changes clearly depends upon the size of the depression and upon its rate of travel, but a period of 24 hours is quite normal.

It should be noted that the winds on the north side of a depression are, generally, less strong than those on the south side so far as the northern hemisphere is concerned, it being usually the case that the isobars on the north side are less crowded than those on the south. A depression passing to the south of the observer generally brings less wind, but more rain and greater gloom, than does one passing to the north.

If high clouds occur, they are generally travelling outwards from the centre of the depression. Thus a southerly wind on the surface, with high cirrus moving from a westerly point, is almost a certain sign of a depression situated to the westward of the observer.

86. *Highs or Anti-Cyclones.*—Anti-cyclones are the contrary to depressions. Here, the maximum pressure occurs in the centre of the closed isobars which are approximately oval or circular in shape. An example of an anti-cyclone will be seen in the lower left-hand corner of Fig. 10. The great distinction between the winds and weather experienced in an anti-cyclone to those experienced in a depression is that the latter are often violent whilst those in the former are very rarely so. Moreover, anti-cyclones travel much slower and more irregularly than do depressions, and, in fact, seem more stable, often remaining more or less stationery for several days. It will be recognised from an application of Buys Ballot's Law that the winds in an anti-cyclone blow clockwise round the centre of high-pressure. This should be compared with the wind-blow round a depression.

In summer, anti-cyclones generally bring fine, calm weather during the day with much sunshine and a high temperature, whilst at night the skies are clear but there is much ground mist or fog.

In winter, however, there seem to be two distinct types of anti-cyclones:—

(*a*) those in which the weather is fine during the day and very cold, with frost or fog, during the night.

(*b*) those in which the sky is persistently covered with low cloud sheets, causing a dullness which is often referred to as "anti-cyclonic gloom."

It used to be thought that the central regions of anti-cyclone were regions of descending currents of air. In the face of the evidence of the persistent low cloud, so characteristic of some "highs," this view cannot be regarded as a correct one. In fact, it seems more true to regard anti-cyclones as comparatively isolated and inert masses of air taking little part in the circulation going on about them; and the fact emerges that almost any kind of weather, except that of a violent nature may be got from them.

It is a fallacy to regard anti-cyclones as, necessarily, areas of fine, balmy weather, a fallacy, however, that seems to die hard.

It seems quite impossible to forecast whether any given anti-cyclone, especially in winter, will be of the blue sky, or the gloomy, type until an actual sample of the particular system becomes available for examination.

87. *Cols.*—A col is the region between two anti-cyclones. An example is shown in Fig. 13.

An examination of the example given will reveal that a col is the meeting place of two sets of winds of different directions ; one set attached to one of the anti-cyclones, and the other set to the other anti-cyclone. These winds are all anti-cyclonic and therefore light. They may, also, be of entirely different temperature and relative humidity. Condensation by mixing is therefore given full opportunity to manifest itself, and fogs and mists are frequent. These fogs and mists are especially marked in cold weather; in warm weather, the mixture of the air streams, with their different physical conditions, makes the development of thunderstorms likely.

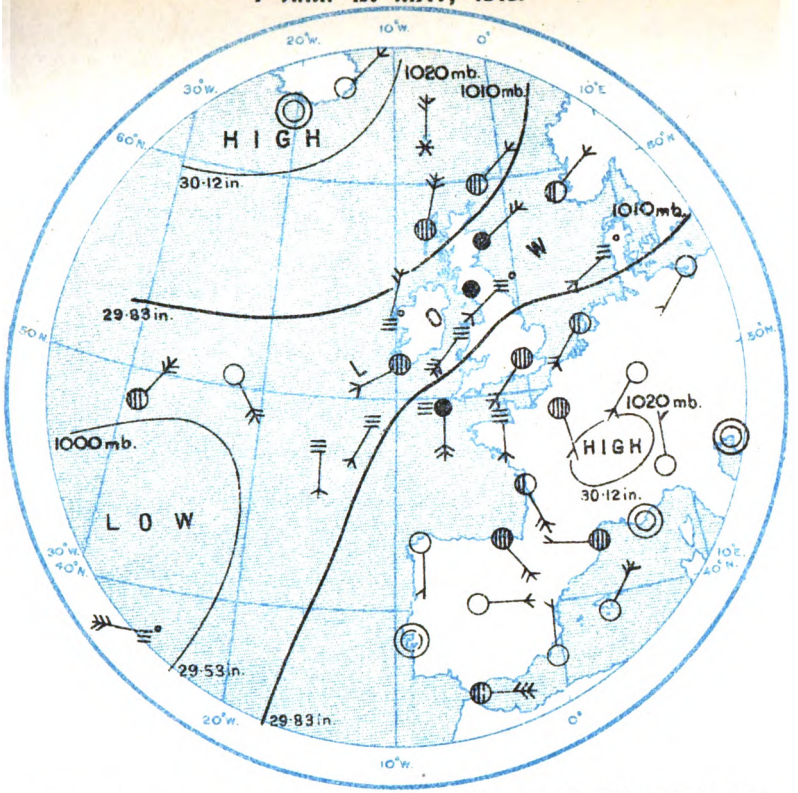
88. *Secondary Depressions.*—Often, on a synoptic chart, a big depression is seen to have one or more smaller depressions on its periphery. Fig. 14 shows an example of a primary depression with a secondary satellite. Sometimes, the secondary grows whilst the primary diminishes, so that from a study of one chart only, without reference to the preceding three or four, it is occasionally difficult to say which is the actual primary and which the secondary. This is the case in the system shown in Fig. 14.

When the secondary depression is fully developed, that is, has its own system of closed isobars, it carries its own wind and weather systems with it. The wind and weather experienced in secondaries are, then, the same in kind as occur in ordinary depressions.

A secondary depression usually travels in an anti-clockwise direction around its primary, and, generally, at a faster rate than does the primary. This means that, as a rule, it progressively alters its relative position with regard to the centre of the primary.

It is interesting to notice the wind behaviour in the region between the secondary and the primary. In Fig. 14, taking the centre over France as the secondary, and the centre over Scotland as the primary, it is obvious that, at some point between the two depressions, the easterly winds due to the northern part of the secondary must balance the westerly ones due to the southern part of the primary, and that, in consequence, a calm should result. This calm in the figure is seen to be in the London area. Such a region of calms or of light variable airs is a feature of the area between a primary and its secondary or secondaries.

DISTRIBUTION OF WEATHER, WIND, AND PRESSURE,
7 A.M. 1st MAY, 1915.



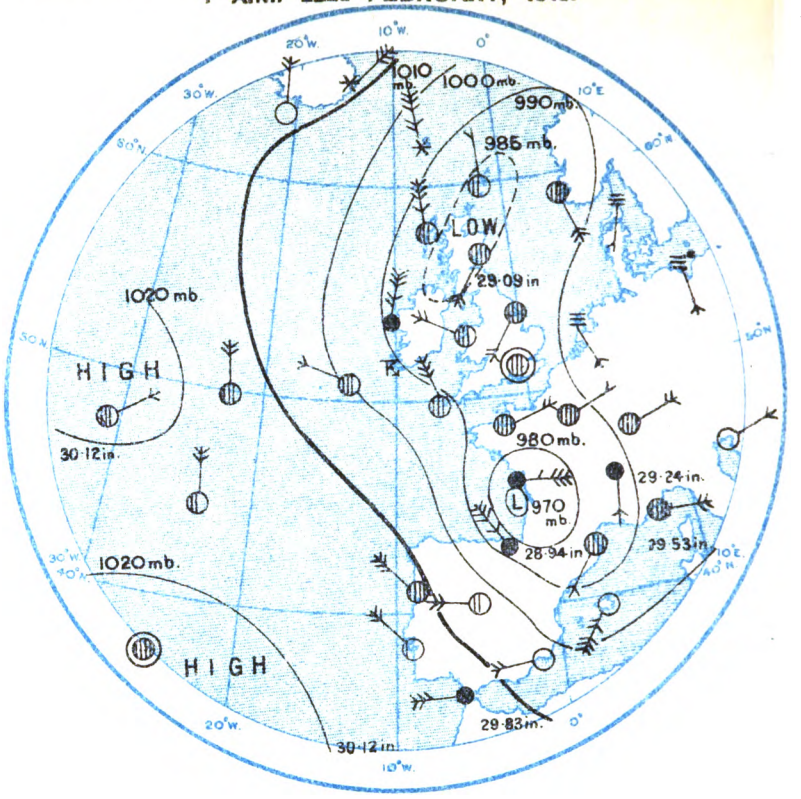
ISOBARS are drawn for intervals of ten millibars.

WIND.—Direction is shown by arrows flying with the wind.
Force, on the scale 0-12, is indicated by the number of feathers.
Calm ◯

WEATHER.—Shown by the following symbols —
◯ clear sky. ◐ sky ¼ clouded.
◍ sky ½ clouded. ◍ sky ¾ clouded.
● overcast sky. ● rain falling
✱ snow. ▲ hail. ≡ fog.
≡° mist. ϒ thunder. ϒ thunderstorm.

Fig. 13.

DISTRIBUTION OF WEATHER, WIND, AND PRESSURE,
7 A.M. 22nd FEBRUARY, 1915.



ISOBARS are drawn for intervals of ten millibars.

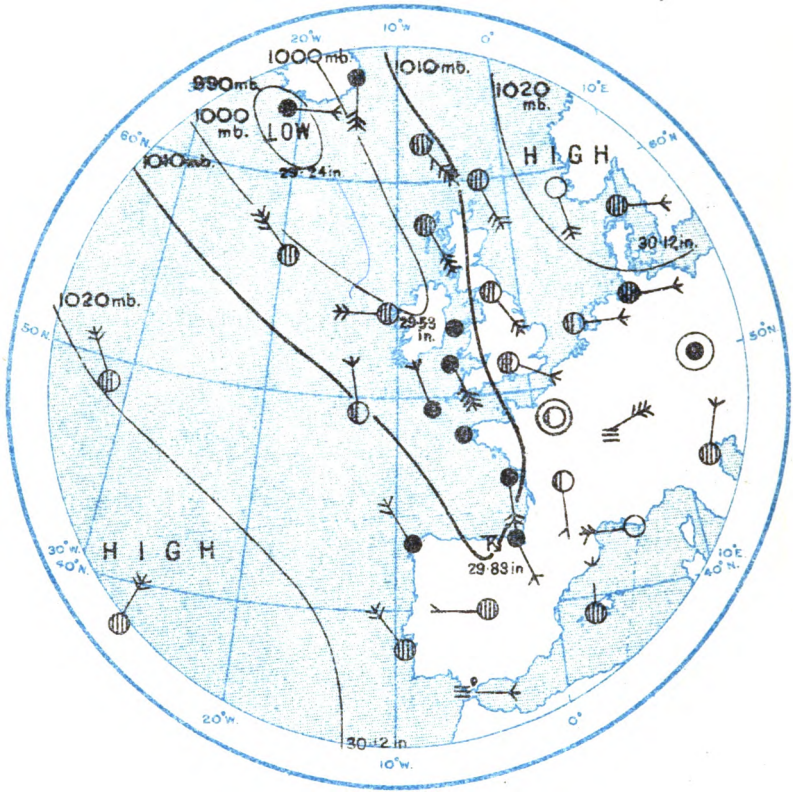
WIND.—Direction is shown by arrows flying with the wind.
Force, on the scale 0-12, is indicated by the number of feathers.
Calm ◯

WEATHER.—Shown by the following symbols —
◯ clear sky. ◐ sky ¼ clouded.
◍ sky ½ clouded. ◍ sky ¾ clouded.
● overcast sky. ● rain falling
✱ snow. ▲ hail. ≡ fog.
≡° mist. ϒ thunder. ϒ thunderstorm.

Fig. 14.

V-SHAPED DEPRESSION.

DISTRIBUTION OF WEATHER, WIND, AND PRESSURE, 7 A.M. 8th OCTOBER, 1915.



ISOBARS are drawn for intervals of ten millibars.

WIND.—Direction is shown by arrows flying with the wind.

Force, on the scale 0–12, is indicated by the number of feathers.

Calm

WEATHER.—Shown by the following symbols :—

clear sky. sky ¼ clouded. sky ½ clouded. sky ¾ clouded. overcast sky. rain falling. snow. hail. fog. mist. thunder. thunderstorm.

Fig. 15.

M.S.O. Press, Kingsway, W.C.2.

S.O.P.P.S. '8595/432. Wt. 8498. D 6216. 3000. 11/21

In summer time, secondary depressions are apt to form in comparatively large numbers. Being shallow, they do not occasion much wind, but usually bring heavy rain and are often the scene of thunderstorms.

Up to the present, only fully developed secondaries, those with their own systems of closed isobars, have been considered. Very frequently, however, the secondary depression is only represented by a sinuosity in the isobars, the sinuosity taking the form of a bulge, the bulge being outwards from the centre of the main "low." These sinuosities travel forward in the same direction as the main depression, sometimes with the same speed, sometimes faster, and carry with them their own alterations of wind and weather, which alterations are, often, very marked. Such "bulges" are usually accompanied by much low cloud and some rain. The important alterations produced by even comparatively slight bulges call for great care in the drawing of the isobars on synoptic charts. These bulges often being otherwise unexpected gales on the side remote from the primary depression.

89. *V-shaped Depressions.*—V-shaped depressions may be regarded as half-way between "bulges" and fully developed secondaries. An example is shown in Fig. 15.

The point of the V in such a depression is generally directed towards the south-east. The eastern side of the depression is marked by southerly winds, much low cloud and rain, and the western side by north-westerly winds, fair weather, and a lower temperature. The change is often very abrupt and is accompanied by squalls. It is clear that a V-shaped depression affords an example of warmer air, that from the south, being forced to rise over colder and denser air, that from the north-west. The southerly winds are usually of high relative humidity so that the dynamical cooling caused by their forced elevation is amply sufficient to produce the low cloud and the rain which so characterise one side of the system.

90. *Wedges of High Pressure.*—Between two depressions there occurs, generally, what is known as a "wedge" of high pressure. The wedge is usually shaped like an inverted V, and it moves in an easterly direction with the two depressions which it separates. As would be expected from what has been said about depressions, the eastern, or front, side of a wedge is a region of fair weather with light northerly or north-westerly winds, and the western, or rear, side, a region of southerly winds and increasing cloud as the second depression approaches. In the centre of the wedge winds are very light and variable. If fine weather quickly follow a depression, it is frequently the sign of a wedge; in which case, bad weather will follow again comparatively quickly.

91. *Straight Isobars.*—Quite often, the isobars on a synoptic chart run almost straight over a large area. Such straight

isobars are, usually, the outermost margins of a large depression whose centre is located a considerable distance away. The winds approximately follow the lie of the isobars and their direction is determined by the position of the centre of low pressure. Almost any type of weather may accompany straight isobars, largely dependent upon the direction of the parallel isobars, their relation to the depression centre, and the season of the year. For example, in winter, in the British Isles, straight north-south isobars bring northerly winds with squalls, and sometimes snow or sleet; but in summer, cloudy and thundery conditions often prevail with an entirely similar isobaric arrangement.

The commonest type of straight isobars over the British Isles is the "south-westerly," which is the one in which the isobars run practically parallel from south-west to north-east, with the centre of the big depression, of which the isobars form a part, somewhere in the Icelandic region. Straight isobars of this type are very favourable to the formation of secondary "bulges." The weather under these south-westerly conditions varies considerably, from fair or fine to overcast with showers, and, sometimes, steady rainfall is even experienced.

CHAPTER XV.

Special Phenomena.

92. *Line Squalls.*—A line squall is a heavy squall of wind which is accompanied by the passage of a long arch of low, black cloud, which often stretches in approximately a straight line for several miles, and from which heavy rain or hail falls for a short time. Thunder, too, is often heard. The squall is also accompanied by a veer of wind from some southerly or south-westerly point to a westerly or north-westerly one accompanied by a sudden drop in temperature and a sudden rise of the barometer. The actual squall of wind lasts for only a few minutes, but is extremely violent.

The phenomena accompanying a line squall are quite characteristic and cannot be mistaken.

The explanation of such a squall is to be found in the sudden undercutting of a warm southerly air current of high relative humidity by a colder, and hence, denser westerly or north-westerly one. The warmer, southerly current is forced to rise abruptly over the colder one. The ascent is accompanied by the dynamical cooling which is an inevitable result of such elevation. As the warmer current coming from the south is generally of high relative humidity, very little ascent—that is. very little cooling—is sufficient to produce low cloud and rain As the undercutting takes place along a long length of line, the

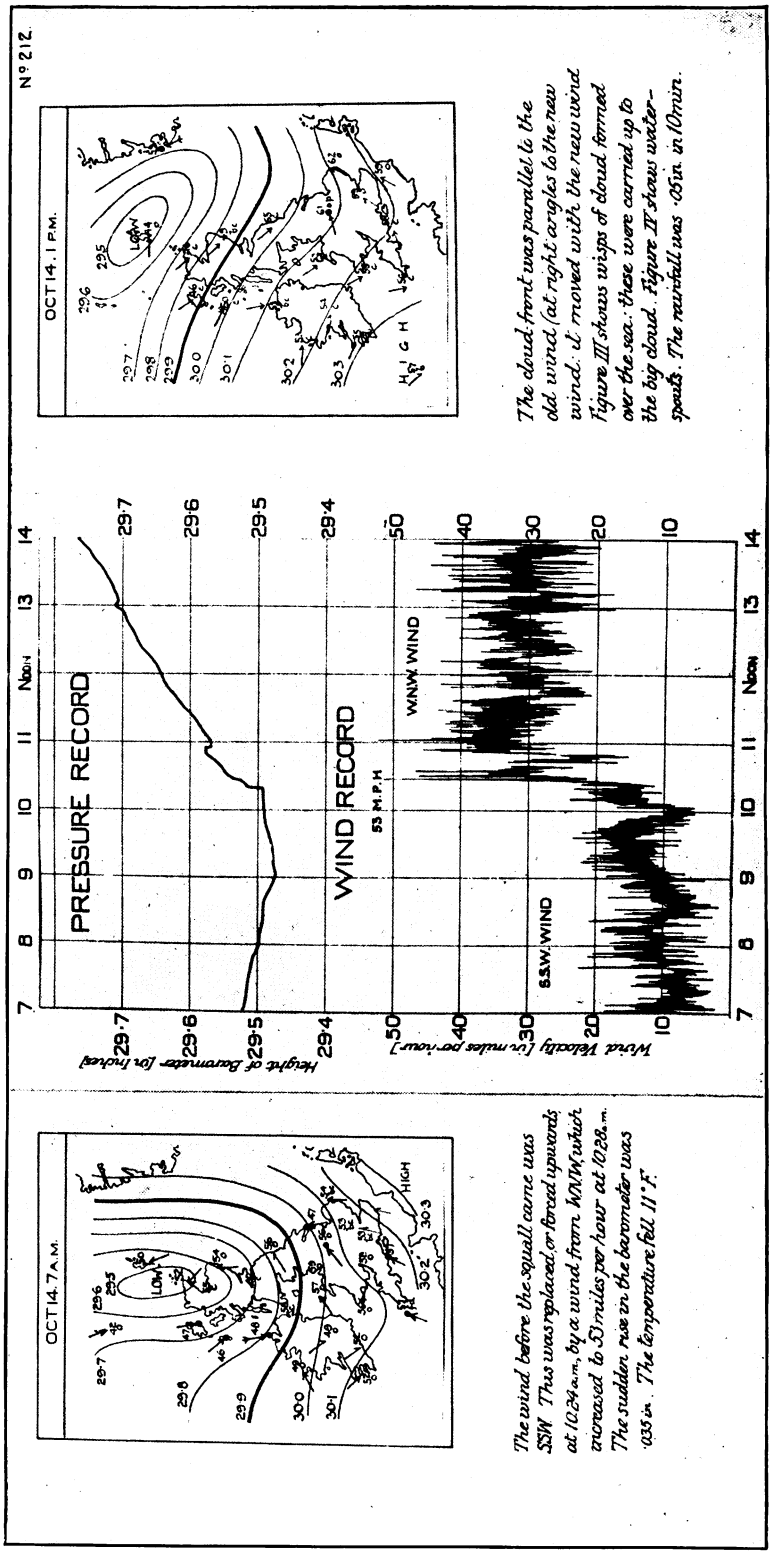

N° 212
OCT 14. 1 P.M.
OCT 14. 7 A.M.
PRESSURE RECORD
WIND RECORD
53 M.P.H
WNW WIND
SSW WIND
Height of Barometer (in Inches)
Wind Velocity (in miles per hour)
7 8 9 10 11 Noon 13 14
29·7
29·6
29·5
29·4
50
40
30
20
10
LOW
HIGH
The cloud front was parallel to the old wind (at right angles to the new wind). It moved with the new wind. Figure III shows wisps of cloud formed over the sea: these were carried up to the big cloud. Figure II shows water-spouts. The rainfall was ·05 in. in 10 min.
The wind before the squall came was SSW. This was replaced, or forced upwards, at 10.24 a.m., by a wind from NNW, which increased to 53 miles per hour at 10.38 a.m. The sudden rise in the barometer was ·035 in. The temperature fell 11° F.

Fig. 16.—Line Squall which passed Aberdeen between 10h. 24m. and 10h. 30m. in the forenoon of October 14, 1912. Maps and records of pressure and wind.

long, black arch of cloud is explained. The violence of the uprush is sufficient to explain the heavy rain, and also the hail (*see* section 53), which is so often a feature of line squalls. The sudden decrease of temperature is due to the fact that a colder air stream has replaced a warmer one on the surface, and this, too, explains the sudden rise in pressure.

The isobaric distribution which ends in the development of line squalls will be revealed by a reference to Fig. 16, which shows the synoptic charts for 7 a.m. and 1 p.m. on October 14, 1912, on which day a line squall crossed Great Britain. It will be noticed in the 7 a.m. chart that northerly or north-westerly winds were blowing down the western coast of Scotland, whilst south-westerly winds were blowing across Southern Scotland. The line of meeting of these two air streams of considerably different temperature was marked by a land squall and all its attendant phenomena. The wind and pressure "traces" taken at Aberdeen on the day in question are also shown in Fig. 16, and should be carefully studied in the light of what has already been said.

Line squalls are most frequent near the trough line on the southern sides of depressions, and are especially liable to happen if the depressions be at all V-shaped, for then, the two wind streams, the one southerly and warm, the other, north-westerly or westerly and colder, are brought more abruptly into conjunction.

Line squalls constitute an exceptionally serious menace both to shipping and to aircraft. Happily, however, once one appears it is regular in its habits and travels steadily from west to east, or from south-west to north-east, with a velocity of 20 to 30 miles per hour ; and hence, due warning of its coming can be given to localities in their track. It is interesting to notice that not one line squall has yet been known to travel from an easterly point to a westerly one.

93. *Thunderstorms.*—All the features of thunderstorms point to their dependence upon a convectional overturning of the atmosphere. They have been grouped* into three main classes :—

(*a*) Those due mainly to heated surface air in fine summer weather.

(*b*) Those associated with powerful upper currents from the south-west, the surface wind being light, variable or south easterly.

(*c*) Those associated with low temperature in the upper air, chiefly in the south-westerly currents of depressions.

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* "Professional Notes No. 8. Temperature and Humidities in the Upper Air conditions favourable for thunderstorm development, and Temperatures over Land or Sea." By Capt. C. K. M. Douglas. Issued by the Meteorological Office, Air Ministry, London, 1920.

This classification is, probably, not thoroughly comprehensive, some thunderstorms occurring which seem to find no place in it, but it is very useful.

Thunderstorms of type *a* occur chiefly in the warmer regions of the earth during the warm seasons, and they are most violent or active at that time of day, three or four o'clock in the afternoon, when the convectional up currents, due to the great heating of the land, are likely to have reached their maximum, The clouds characteristic of these summer thunderstorms all point to the importance of the convection currents engaged. The cumulus clouds of an ordinary summer's morning are seen to develop upwards. The development is continued and, soon, some of them reach towering sizes, their summits attaining heights up to 20,000 feet. If the summits of these largely developed clouds be watched, a curious change is seen to take place, the tops seeming to become flattened and then covered with wisps or filaments of cirrus-looking cloud, termed "false cirrus" which cover them as with fleecy mantles. Investigation has shown that the "false cirrus" is made of snow.

It is not every cloud present which goes through the full development outlined. When the full development is reached the whole appearance of the "thunder cloud," as it is called, is that of an anvil of great size which has been covered with a cloth of exceptionally delicate texture. Generally, a thunderstorm soon follows the appearance of an "anvil cloud."

It will be recognised that the lower the upper air temperatures are, the better are the conditions for the development of these summer thunderstorms.

Thunderstorms of type *b* are due to a definite flow of cooler air over warmer, instead of to direct heating of the land surface. Generally a warm surface southerly or south-easterly current is overlain by a cooler south-westerly one. In such cases the curve representing the fall of temperature upward is very distorted and atmospheric instability is set up. Especially does this seem to occur in the south-east quadrants of depressions. There the surface wind is south-easterly or southerly, and in this country warm and of comparatively high relative humidity. It is known, too, that the upper winds in those quadrants are mainly south-westerly or westerly, and of lower temperature and relative humidity. It becomes clear, therefore, that here opportunities for convectional overturning exist, over and above that afforded by any local heating of the ground.

Thunderstorms of this type seem frequent and it may be due to their prevalence that, as a matter of statistics, thunderstorms occur more frequently in the south-east quadrants of depressions than in any other isobaric grouping. It is worthy of notice, too, that the conditions outlined may occur during the night as well as during the day, and that thus some nocturnal thunderstorms may doubtless be explained.

Thunderstorms of type *c* are associated with the very low upper air temperatures which are known to exist in the southern part of a depression. If then the surface southerly or south-easterly currents of the south-east part of the depression be fairly warm, their displacement by the colder air from above may cause conditions suitable for thunderstorms. Generally thunderstorms of this type are not violent, and the conditions suitable for their development may occur either during the night or day.

In view of what has been said in the consideration of the three types of thunderstorms, it is interesting to notice that in such a region as Iceland most of the thunderstorms which occur are nocturnal, and, moreover, characterise the winter months more than the summer ones. In such high latitudes it would appear then that the effect of local heating of land surfaces is seldom sufficient to produce thunderstorms; and that the storms there are mainly produced as a result of the conditions outlined in the consideration of thunderstorms of types *b* and *c*.

94. *Cloud-bursts.* — Cloud-bursts are only exaggerated thunderstorms. They occur chiefly in hilly or mountainous districts, and manifest themselves as exceptionally heavy rainfalls (sometimes with hail) in very short periods of time. They are probably caused by the sudden stoppage of ascending air currents as the hills or mountains are crossed. As was shown in section 50, an ascending air current of sufficient velocity is able to support a great quantity of accumulated water or hail in it. If this upward current be suddenly stopped the water, which it had been supporting, falls, and if the accumulated stores were great the fall is extremely heavy and rapid.

95. *Tornadoes.*—A tornado may be defined as a very violent but short-lived wind. The connotation of the name varies somewhat in different parts of the world. In West Africa the tornado is the squall which blows out of the front of a thunderstorm at about the time the rain commences. Similar squalls occur in all parts of the world associated with thunderstorms.

In the United States of America the name "tornado" is applied to the small but very violent whirlwinds of one or two hundred yards in diameter which advance towards the east or north-east at a speed of from 20 to 40 miles per hour, the very strong winds destroying practically everything within the direct path. The activity of one tornado lasts for about half an hour, and, apart from the violent winds, the most characteristic feature of these tornadoes is the funnel-shaped cloud which hangs downward and is generally in a whirling condition.

Tornadoes especially favour the valley of the Mississippi and occur chiefly on hot afternoons in the summer months. They occur most frequently in the south-east quadrants of depressions, about 500 miles from the centre of lowest pressure.

Waterspouts are the funnel-shaped tornado clouds occurring at sea. They occur more frequently in the tropics than elsewhere. The funnel cloud descends, and, as it descends, a cloud of spray or vapour forms over the sea immediately beneath the point of the funnel. Finally, the funnel point touches the surface and the cloud of spray or vapour takes on the appearance of a column of water. Like the tornadoes on land, waterspouts last only for about half an hour.

96. *Hurricanes and Typhoons.*—Tropical depressions are often of small diameter, from 50 to 300 miles, with very steep pressure gradients, and consequently with winds circulating around them of great violence. Such systems occurring in the Western Pacific, near Japan and the Philippine Islands, are termed "typhoons"; if near the West Indies, "hurricanes"; and, if in the Indian Ocean, "cyclones." The use of the term "cyclones" in this connection needs to be carefully differentiated from the usual use of that term in Great Britain (*see* section 79).

Hurricanes, typhoons, or "cyclones" are accompanied by great masses of cloud, from which rain falls in torrents, and very strong winds which, however, are not quite so violent as those experienced in tornadoes.

The systems move along fairly regular routes in a mainly westerly direction. If land be encountered the storms weaken and often die away.

One peculiar feature of a hurricane or typhoon is the well marked nature of the centre. As the hurricane travels the wind rages with great violence, but, in the centre, drops to almost a dead calm. This change occurs abruptly and the clouds may even break and blue sky appear. The diameter of the calm area may be from 10 to 30 miles. As the hurricane continues to travel, however, and the centre passes over the observer away to the eastward, the winds rise again as abruptly as they dropped, attaining quickly to a violence equal to that which they had before but blowing now from the reverse direction, as would be expected from Buys Ballot's Law. The centre, on account of its peculiar characteristics, is often referred to as "the eye of the storm," and has been termed, poetically, "the whirlwind's heart of peace."

97. *Pamperos.*—South America, especially the republics of Argentina and Uruguay, is often the scene of fierce thunderstorms, which are termed "pamperos." Pamperos are line squalls and show all the characteristics of those disturbances (*see* section 92). The squalls brush up great clouds of dust from the dry pampas and are accompanied by drenching rains and almost incessant lightning for a short period. These storms are greatly feared by sailors in the estuary of the Rio de la Plata.

CHAPTER XVI.

Forecasting.

98. *Forecasts.*—The first use of synoptic charts for forecasting weather was made by Admiral Fitzroy in 1860, and it was he who invented the special meaning of the term "forecast" to avoid the doubtful connotations attaching to such terms as "prognostic" and "prophecy."

As issued now, a forecast generally covers a period which is not greater than 24 hours, and, usually, a statement under the heading of "further outlook" is added, giving the conditions likely to be experienced in the 24 hours or so following the period covered by the actual forecast.

A forecast is published, as a rule, in a definite form. It includes :—

(*a*) A statement of the wind speed and direction at a height of 2,000 feet, together with the changes therein likely to occur during the period of the forecast.

(*b*) A similar statement with regard to the wind at the surface.

(*c*) A statement concerning the probable state of the sky face with regard to cloud, together with statements concerning the incidence of precipitation (if any) and concerning the temperature likely to be experienced, especially as to whether that temperature is likely to be greater or less than the normal for the time of year. Notes are also added, if necessary, as to the probability of thunderstorms, or frosts, or any other special phenomena.

(*d*) A statement concerning the visibility likely to be experienced together with notes, if necessary, concerning the probability of the occurrence or clearance of mists and fogs.

The "Further Outlook" is then appended in one or two short but comprehensive sentences.

99. *The Practice of Forecasting.*—In the making of such a forecast as has been described. the forecaster depends practically entirely upon the synoptic charts before him, together with special experimental data received from certain stations concerning upper air winds and temperatures. He examines the current chart and determines what types of isobaric distribution (*see* section 78) are present. From a further consideration of the chart, in conjunction with the two or three previous charts, he then determines the probable travel of the various isobaric groupings present, and tries to visualise what the synoptic charts of 6 and 12 hours hence will be like. Knowing the general sequences of wind and weather connected with the

various types of isobaric distribution, he is then able to make up his mind as to how far the particular regions for which he is forecasting will be affected by the various sequences in their travel.

The weather and wind connected with the various pressure types, together with notes upon the travel of those types, will be found in Chapter XIV.

To determine the probable visibility, and the probability of the occurrence of such phenomena as hail, thunderstorms, frosts, and the like, the forecaster has to bear continually in mind the physical principles underlying those phenomena, which principles have been considered at more or less length in previous sections of this book.

To determine what the "further outlook" is likely to be, he has to visualise what the synoptic chart is likely to be 24 hours hence, and thence to apply the same plan that has already been outlined.

It will be recognised, then, that the making of a sound weather forecast is by no means an easy matter, but connotes that the forecaster shall have at his ready disposal a well organised stock of meteorological and physical knowledge, which knowledge can only be obtained by diligent study, and the ability to use which can only be gained as the result of much practice. The forecaster is much in the position of a physician; to be successful he must be able to diagnose rapidly but soundly, must be able quickly to determine which factors are essential and which non-essential, and then having gained the factors by his diagnosis, his analysis must be able to predict the future action of those factors, and to interpret that action in the light of his particular needs.

Forecasting weather is a scientific process based upon physics and soundly sifted experience; it cannot be successfully accomplished either by reading the legends around a "weather glass" or by an appeal to the rhymes and maxims of weather lore, no matter how extensive may be the stock of that weather lore held.

100. *Forecasting by a Single Observer.*—It is interesting to attempt to realise what a single observer, without any synoptic charts or without any knowledge of what weather conditions are in other localities can do to forecast coming weather.

Remembering Buys Ballot's Law, and what has been said about the wind and weather sequences in a depression (*see* section 85), and also by watching his barometer, he should be able generally to recognise the approach of a depression, and also to determine how he is situated with regard to the path of travel of its centre. Once knowing this, he is able roughly to forecast coming weather events in the next few hours, though he will be very considerably handicapped, in the absence of a

current chart, by not knowing the size of the depression with which he is dealing.

He may often, too, be able to tell whether fine weather is the result of a wedge or of an anti-cyclone, and a study of the principles underlying the formation of fog (*see* sections 36–40), and of frost (*see* section 34), may enable him quite often successfully to predict whether or no those particular phenomena are to be expected. A careful study of cloud forms, especially of alto-cumulus-castellatus and of "anvil cloud," may enable him, too, to be successful in forecasting some thunderstorms.

But when all is said, the best that a single observer can do to forecast, for even a short period, is very little, and "further outlooks" are quite impossible for him. In short, synoptic charts are the very foundation of successful forecasting, and, without them, very little is possible.

101. *Long Range Forecasts.*—Much work has been done in the endeavour to find means to forecast the coming of weather changes at a greater distance ahead than three or four days. It cannot be said that, up to the present, very much success has resulted.

If the problem be put in the shape of asking what the weather in such a place as London, for example, will be this day week, then the only answer is that the succession of pressure types is, apparently, so irregular that the weather at such a distance ahead cannot be forecasted beyond giving the average for the time of year. There are almost certainly laws underlying the apparently irregular succession of isobaric groupings, but they have not yet been found, though probably they will be in course of time. Three or four days ahead, in such a region as the British Isles, seems the extreme distance for which a forecaster can predict satisfactorily, even under the most favourable conditions.

But certain results have been reached with regard to a periodicity in the sequence of certain meteorological elements, results which are sufficiently encouraging to lead to hopes that much more may yet be done. To take an example, Brückner, of Berne, so far back as 1890, concluded, from an examination of all available rainfall data, that, in Europe, there is a variation of rainfall with an average period of 35 years, and hence, was able roughly to predict wet periods and dry periods, each approximately of 17 years' duration. Russell has suggested, similarly, a period of 19 years for the variation in the rainfall of Australia, a result which has been confirmed by other workers.

Much, too, has been attempted in the correlation of sun-spots with terrestrial weather. The mean period of frequency of sun-spot numbers is, approximately, 11 years. It is known that sun-spots are due to vertical disturbances in the sun's atmosphere, such disturbances being of huge extent. It is

known, too, that the spots bear a definite relation to terrestrial magnetic records. Many weather phenomena such as "cyclones" in the Indian Ocean (*see* section 96) and the rainfall in Scotland have been endeavoured to be correlated with the periods of the spots, but the results have not been very satisfactory.

Another method of employing meteorological statistics is to endeavour to prove a connection between one set of phenomena occurring in one part of the world and another set of different phenomena occurring in another part at a later date, thus placing the two in the form of cause and effect. As all weather is, doubtless, the result of a general atmospheric circulation over the whole globe, little objection on the logical side can be urged against these attempts, and some have been very successful. Sir Napier Shaw* has shown, for example, that a remarkably close parallelism exists between the seasonal variation in the trade wind at St. Helena and the rainfall in the south of England; and several other workers like Meinardus and Hildebrandsson have gained similarly noteworthy results.

But there is a danger to be avoided and this section cannot be better concluded than by a quotation which reveals the limitations of these periods as applied to actual forecasting for a given stretch of time or for a given date. The quotation† is as follows:—"There is at once a fascination and a curious inconclusiveness about many of these attempts to identify the period of variation of the meteorological elements. The periodicity shows itself when records for long intervals are studied, but it is apt to be illusory as a guide to the meteorological character of any particular year. An example of the fascination and the difficulty here referred to may be given from the consideration of the seasonal variation of rainfall in our own country. Nothing is more certain about the seasonal variation of that element than that the rainfall tends to a maximum in October and a minimum in March; any curve of average monthly values taken for a long period of years with give that result, and, consequently, one is perfectly justified in assuming that the assignment of a seasonal periodicity in rainfall with a maximum in October represents something real, yet, if one were to hazard a prediction that the coming month of October will be the rainiest month in the current year, the facts might belie the prediction."

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* *See* "Nature," Vol. 73, p. 175.

† "Forecasting Weather." Sir W. Napier Shaw, F.R.S. (Constable and Co., Ltd.) 1913. Chapter XVII. p. 357.

CHAPTER XVII.

Weather Lore.

102. *Weather Maxims.*—Ever since man has thought at all, he has generalised about the weather with the result that a very large number of weather maxims are now in existence, these maxims being intended as means whereby the weather to come may be forecasted.*

A few of these maxims are true, a larger number contain a partial truth, a very large number indeed, are completely fallacious, and some are mutually contradictory. But this does not seem to matter at all; these maxims are part of the popular current coinage of conversation, and often enough, definite action is based upon them, which definite action leads frequently to a failure which need not occur if the user of the weather maxim but take the trouble to examine the foundations of the belief in which he puts his trust.

Very few of the common weather sayings stand the test of statistical examination, and this is hardly a matter for surprise when the propensity of man to count the "hits" and to neglect the "misses" be remembered.

Consider the prediction, for example, associated with St. Swithin's Day (July 15th) in England :—

> "If St. Swithin greets, the proverb says,
> The weather will be foul for forty days."

Even the most cursory investigation of this over a few years demonstrates its unreliability. There is a further point about this saying, however, which is interesting and that is, that other nations close at hand have similar predictions connected with other saints and other days. In France the day of augury is that of St. Medard (June 8th), in Belgium that of St. Godelieve (July 27th), and in Germany that of the Seven Sleepers (June 27th). It is clear, therefore, that giving to each of these predictions equal value, in quite a circumscribed portion of Western Europe it would be foul weather continuously for a very long period, a doctrine to which even the most inveterate grumbler concerning the weather could hardly truthfully subscribe.

Sayings concerned with the weather likely during a given month are often equally unreliable. For example, the second of the months of the year is frequently referred to as "February Fill-dyke," this being, presumably, a statement of belief in it as a time of much rain; but, as a matter of statistics spread

* The interested student is referred to "Weather Lore. A Collection of Proverbs, Sayings, and Rules concerning the Weather." By R. Inwards. 3rd edition, 1898.

over a long period, February in the British Isles is one of the driest months in the year. An examination, too, of actual months of March over long periods reveals the fact that no reliance whatever can be placed on the couplet—

"March, black ram,
Comes in like a lion and goes out like a lamb."

Many sayings, too, are in existence that endeavour to show a connection between the weather in one period of the year and that in another, such as that which declares that if the end of October and the beginning of November be wet, then the January and February following will be frosty and cold, except after a very dry summer, but statistical investigation has shown clearly that such sayings have very little in them.

There is a great number of sayings existing which endeavour to relate the behaviour of wild and domestic animals to weather and its changes. Some of these sayings depend simply on the response of the animals in question to the weather actually existing at the moment, and, as such and limited to such, some reliance may be placed upon them, especially is this so in the case of considerable changes in humidity as both men and other animals are affected by the change from dry to wet air, and *vice versâ*. But this is an entirely different matter from attributing to animals a foresight, in the case of coming weather, denied to man. Such a foresight has never been proved. To take an example, investigation has shown that no reliance at all can be placed upon the supposed instinctive foresight of such animals as beavers and squirrels in preparation for severe winters.

Another very popular belief is that the phases of the moon are able to exert an influence upon terrestrial weather, but this, too, has never been demonstrated as having an objective reality to the satisfaction of meteorologists.

In some of the sailor's weather maxims, however, more truth can be found, for these can often be related to the types of pressure distribution appearing on synoptic charts. For example, the saying—

"First rise after low
Foretells a stronger blow,"

is quite true of the squalls and general increase in wind velocity which are often experienced as the trough line (*see* section 80) of a depression passes. Similarly, the couplet—

"Long foretold, long last;
Short notice, soon past,"

is often true, inasmuch as the larger depressions with their larger areas of bad weather travel more slowly, as a rule, than do the smaller depressions; and, therefore, their warning signs of high cloud and backing winds are in evidence for a longer time.

In the land saying—

"Rain before seven,
Fine before eleven,"

there is sometimes truth as it is usually connected with the passage of a small secondary depression. Similarly, the fact that depressions often follow one another quite closely lends point to the saying that—

"A Nor-wester is not long in debt to a Sou-wester."

But it cannot be too strongly emphasised that even those sayings that can be connected with synoptic charts are simply general statements to which many exceptions occur. Halos, for example, around the sun or moon are generally regarded as signs of coming bad weather, and as they are a concomitant of cirro-stratus and cirro-nebula clouds, which clouds are a feature of the fronts of depressions (*see* sections 81 and 85), the belief has a good deal of truth in it; but high clouds with halos sometimes occur in the rear of depressions when they cannot be considered as a sign of bad weather but of quite the reverse.

Many sayings relate to sky colorations in their relation to weather. There is, for example, the very well known one—

"A red sky at night
Is the shepherd's delight;
A red sky at morning
Is the shepherd's warning,"

which often gives reliable prognostications but, on the other hand, quite often proves "a broken reed."

Rainbows deserve some reference in this connection. By reason of the physics of their formation, the centres of rainbows are always exactly opposite the sun. In regions therefore where areas of rain generally travel from westward to eastward, as in the British Isles, rainbows give some indications of coming or departing rain; for rainbows in the east, and hence in the afternoon, denote clearing weather, the rain forming the bow having passed the observer, but if seen in the west, and therefore in the morning, rain is approaching.

In short, no weather maxim should be accepted, no matter how popular or how often quoted it may be, unless it has been subjected to statistical investigation, including, if possible, a comparison with many synoptic charts, over a long period and has not been found wanting. Very few maxims can survive such a searching test, as has been already said, and must be regarded as unworthy of modern acceptance. It is a complete fallacy to believe, as so many people do, that just because a thing is often said that there is, therefore, something of truth in it.

103. *The "Weather Glass."*—In the period between the invention of the barometer (1643) and the introduction of the synoptic chart (about 1860), the weather maxims handed down from antiquity were reinforced by personal observations of the barometric pressure. It is no matter for surprise, therefore, that

the period in question was characterised by most persistent attempts to interpret barometer readings in terms of coming weather. The "weather glass" was one of the results: and, as used now, usually consists of a mercury or aneroid barometer, the height of which is indicated by a hand moving over a dial inscribed with legends which run as follows:—Very Dry, Set Fair, Fair, Change, Rain, Much Rain and Stormy.

These legends are obviously not very satisfactory because they are written against particular readings of the barometer irrespective of locality or the height of the instrument above sea level. Moreover, if synoptic charts impress one fact upon the student of them more than another, it is that it is the relative distribution of pressure which is the all-important matter, and not the actual barometer reading at any one place. Nevertheless, the legends and their positions are based upon experience and, hence, are not without value; but they alone are not sufficient to give sound forecasts in the absence of synoptic charts.

An extension of the legends on the "weather glass" is to be found in the comprehensive list of instructions* for the use of the barometer to foretell weather, issued by Admiral Fitzroy in about the year 1860. Once again these rules are based upon wide experience, and, consequently, give often enough sound results. The coming of synoptic charts has, however, thrown an entirely new light upon weather and its changes, and Fitzroy's rules can now only be recommended for use in those circumstances when it is impossible for the inquirer either to draw and interpret a synoptic chart for himself, or to get, by wireless telegraphy or otherwise, a forecast based upon such charts.

PART III.—THE UPPER AIR.

CHAPTER XVIII.

The Variation of Wind with Altitude.

104. *A Note on Units.*—Any discussion on what may be termed "aerology", the study of the upper air, introduces afresh in an acute form the question of units. A previous reference bearing on this vexed question in present-day meteorology has been made in section 69.

The subject of units is more acute in the study of the upper air for various reasons. In the first place, the study is a comparatively new one and practically all the work in it has been done, and the results published, in C.G.S. units (*see* section 69); heights being measured in metres or in kilometres,

* Reprinted in "The Weather of the British Coasts," issued by the Meteorological Office, London.

velocities in metres per second, and temperatures in degrees Centigrade (or, more generally, marking another diversity, in degrees Absolute). This means that any writer, writing for English readers and, hence, desirous of using the units familiar to those readers, that is to say, putting heights in feet, velocities in miles per hour, and temperatures in degrees Fahrenheit, has to change the data of the various original publications into the English units. The transformations obviously lead to awkward numbers as the scales on the one side cannot be expressed in simple round numbers of the scales on the other.

In the second place, the discussion of such a matter as upper air temperatures on the Fahrenheit scale involves the use of negative signs, and, as has been well said,* "a scale of "temperature including positive and negative signs is dan- "gerous for the observer, troublesome for the computer, "awkward for the printer, and misleading for the reader." The use of the Centigrade scale involves the same trouble, which, however, is avoided if the Absolute† scale be used.

The fact must, however, be faced that the two previous parts of this book have been written using the English units, as those units are at present very much more familiar to the readers for whom it is mainly intended. That being the case, a change of units in the present part seems unjustified as involving a serious break in continuity, and as likely to lead to confusion. Nevertheless, it is extremely desirable that the student should spare no effort to make himself familiar with the C.G.S. system, inasmuch as that is the system in which most research work in the study of the upper air is being published, and as it will ultimately probably come into general use in meteorological science.

A compromise, then, seems the best way. To secure continuity the data and tables appearing in the discussion of upper air conditions which follows will be expressed in English units, but wherever possible the C.G.S. units will be given as well.

It should be noted that, in transformation from one system to another, such matters as a certain number of kilometres will be expressed in an approximate round number of feet, and a certain number of degrees Absolute as a round number of degrees Fahrenheit, decimal points being omitted except where the accuracy denoted by them seems important.

105. *Wind near the Surface.*—The Meteorological Office, London, have issued‡ an interesting table (Table VI.) which

* "Observer's Handbook," Meteorological Office, London, 1919 edition.

† "The measure of temperature is so chosen that the volume of a mass of gas at constant pressure, or the pressure of a mass of gas at constant volume, is proportional to the temperature. It is the temperature on the Centigrade scale increased by 273." ("Observer's Handbook," Meteorological Office, London, 1919 edition.)

‡ Annual Summary of the Monthly Report, 1916.

endeavours to connect the velocity of the wind at heights up to 100 feet (30 metres) above open grass land with that occurring at 33 feet (10 metres).

TABLE VI.

Wind at Various Heights above Open Grass Land compared with Wind at 33 feet (10 metres).

Height in —											
Metres - -	0·5	1	2	3	4	5	10	15	20	25	30
Feet (approx.)	1·5	3	6·5	10	13	16	33	50	66	82	100
Ratio to wind at—											
33 feet (10 metres).	·50	·59	·73	·80	·85	·89	1·00	1·07	1·13	1·17	1·20

A note appended to the table is also interesting. The note reads :—"It is to be understood that the ratios shown above " are only approximate. The increase of wind with height is " more rapid in proportion when the air is not disturbed by " convection, *i.e.*, in cold weather and at night ; it is less rapid " under the opposite conditions."

The note is valuable because it gets at once to the difficulty that is involved in any discussion of winds near the surface. The air near the surface is in a continual state of eddying, the eddies being due to irregularities in the surface of the ground over which the air is moving, and also to changes in the temperature of that surface, and consequently of the air in its proximity. Reference has already been made to these eddies in the discussion of the gustiness shown by anemometer traces (*see* sections 7 and 9).* The effect of these eddies is to promote the mixing of adjacent masses of air and, in general, the lower masses gain in momentum at the expense of the higher ones. If eddying be reduced through any cause, the lower layers become checked by friction with the surface of the land, whilst the upper layers gain by not being subjected to the loss of momentum due to mixture with the lower ones, which are less energetic. Taylor has developed the theory of eddy motion in the atmosphere in two important papers,* to which the student is referred.

In view of what has been said concerning the varying turbulence of the air layers near the ground, it would appear that it is a very difficult matter to find any simple relationship existing between the wind in one layer near the surface and another.

Attempts have been made, however, to find some simple formula which shall accomplish the desired end.

* G. J. Taylor, "Phenomena connected with Turbulence in the Lower Atmosphere." Proceedings, Royal Society, A., Vol. XCIV., p. 147, 1918. "On Eddy Motion in the Atmosphere," Phil. Trans., A., Vol. CCXV., p. 1.

In 1880, Stevenson* gave a formula for approximate wind velocity up to 51 feet. His formula was—

$$V = v\sqrt{\frac{H + 72}{h + 72}},$$

where V = the wind velocity at height H, which is the velocity to be found,

and v = the known wind velocity at height h.

H and h are measured in feet.

Later, in 1885, Archibald,† as a result of observations made with kites, gave a formula for wind velocities between 300 feet and 2,000 feet. It will be noticed that he avoided the layer in immediate proximity to the surface. His formula was—

$$V = v\left(\frac{H}{h}\right)^{\frac{1}{4}}$$

where V, v, H and h, have the same meanings as in Stevenson's formula.

Sir Napier Shaw and Captain Cave, in 1910, as a result of observations on small, hydrogen-filled balloons, put forward the formula‡—

$$V = \frac{H + a}{a} V_o,$$

where V = wind velocity at height H,

V_o = wind velocity given by a well-exposed anemometer,

and a = a numerical constant for the particular site.

The observations were carried out at Ditcham Park, in Hampshire, and the value of the constant a there was 550 feet (167 metres), the height of the station above sea-level.

None of the formulæ mentioned, however, have been found to be entirely satisfactory when compared with actual results.

Some later attempts, too, merit mention. Chapman,§ for example, has put forward an empirical rule that the speed of the wind in the lower layers is a linear function of the logarithm of the height. His formula takes the form—

$$V = a \log H + b,$$

where V is the wind velocity required at height H,

and a and b are constants which not only vary from place to place, but also for different sets of observations taken at different times of the day at the same place.

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* Journal, Royal Scottish Meteorological Society, 1880, p. 348.

† "Nature," Vol. XXVII., p. 243.

‡ First Report, Advisory Committee for Aeronautics, Reports and Memoranda, No. 9.

§ E. H. Chapman, Professional Notes, No. 6. Meteorological Office, London, 1919.

Hellman,* in 1917, gave a very similar formula—

$$V + a \log (H + c) + b,$$

where a, b, and c are constants, and H and V have the same meaning as in Chapman's formula.

106. *Extent of Surface Turbulence upwards.*—It is pertinent, at this point, to inquire as to how far upwards the turbulence attributable to eddy motion extends. In this connection the results obtained from the anemometer placed on the top of the Eiffel Tower in Paris are of great interest. The head of that anemometer is, roughly, at a height of 1,000 feet (more exactly, 305 metres) above the ground and its records reveal the fact that the disturbing effects of the surface certainly extend to that height. It would be expected, too, that the effect of turbulence should be felt at greater heights in summer than in winter, as it is in summer that the temperature cause forming eddies is given its fullest opportunities. The term "surface layers," then meaning the layers affected by surface turbulence, is usually taken to mean the air up to 6,000 feet in winter and up to 9,000 feet in summer.

It must be recognised, however, that even above the level where surface turbulence ceases to affect matters, the atmosphere still remains complex, and that the behaviour of the wind there cannot be expressed in simple statements.

107. *Methods of Measuring Upper Winds.*—The measurement of winds in the upper air, by means other than by that of determination of cloud velocities, is of comparatively recent growth. The measurements are usually made either by following the motions of small hydrogen-filled balloons,† or by observing the smoke drift from shells bursting at known heights.‡ Kites, too, have been used, but are hardly to be compared with the other two methods.

It is clear, however, that both the small balloon and the shell-burst methods are only possible in those conditions when low cloud is more or less absent. A method has been devised whereby the wind at a given height even above cloud sheets can be calculated from the bursting of bombs at that height; but not very much work has been done on it as yet. It will be recognised, therefore, that the means available for determining the wind at heights are limited, and are available only in clear-sky (that is, clear of low cloud) weather. This limitation needs to be borne in mind in what follows.

108. *Wind Velocity between the Surface and* 8,000 *feet.*—This layer includes the surface layers and gives, also, a little information about what is just beyond the height where the surface turbulence is, at times, eliminated (*see* section 106).

* Preuss. Akad. der Wiss., Berlin, 10, pp. 174–197, 1917.

† For details of the methods employed, *see* either "The Structure of the Atmosphere in Clear Weather" by C. J. P. Cave (Cambridge University Press), 1912; or "The Computer's Handbook," Section II., Subsection I., Metereological Office, London.

‡ "The Computer's Handbook," Section II., Subsection I., Meteorological Office, London.

It is best treated by reference to a special set of observations, and the set chosen is that performed by Dobson,* at Upavon, using the small balloon method with one theodolite. The observation ground was 600 feet (183 metres) above sea-level, and was characterised by an exceedingly open exposure.

Dobson arranged his 97 ascents with regard to the wind direction at the surface. With north-easterly surface winds, the gradient wind velocity (*see* section 77) as calculated from the current synoptic charts was reached at a height of about 3,000 feet (915 metres), and then the velocity began to diminish: first, an increase up to 3,000 feet, and then a falling off. With south-easterly surface winds the velocity increased to reach the gradient wind speed at just under 1,000 feet (approximately 300 metres), and then showed little deviation from that value with increasing height. With south-westerly surface winds, the velocity increased to reach the gradient wind speed at about 1,500 feet (approximately 500 metres), and thenceforward continued to increase slightly. With north-westerly surface winds, the gradient wind was reached at just under 1,000 feet (approximately 300 metres), and, thereafter, the wind showed a fairly regular, considerable increase up to the limit of Dobson's observations, namely, 8,000 feet (approximately 2,500 metres).

The general result, then, to be obtained from this work is that mean wind velocity increases from the surface up to about 1,000 or 1,200 feet (roughly 300 to 400 metres), and that, thenceforward, the behaviour is more eccentric, depending to some extent upon the surface direction, and, as he showed in another analysis of the same observations, also upon the strength of the wind. The curves which he drew to illustrate his conclusions show very clearly that the increase of wind speed between the surface and the 1,000 or 1,200 feet level is not linear. This statement should be compared with the various formulæ given in section 105.

It is interesting to notice that similar work done at coast stations reveals that the wind behaviour between the surface and 8,000 feet (roughly 2,500 metres) is even more complicated there than that shown by Dobson's results at Upavon, an inland station. This would be expected as a consequence of the juxta-position of land and sea; the land on the one side with its atmosphere filled with eddies and general turbulence, and the sea on the other with its atmosphere, to a great extent, free from turbulence.

109. *Wind Direction between the Surface and* 8,00 *feet.*— So far as general changes of direction are concerned in this layer, the most marked feature is the "veer" (that is, change of wind in a clockwise direction) from the surface direction. This veer is particularly marked in the first 2,000 feet. The

*G. M. B. Dobson, "Pilot Balloon Ascents at the Central Flying School, Upavon, during the year 1913." Quarterly Journal, Royal Meteorological Society, Vol. XL., p. 123. 1914.

surface wind deviates from the lie of the isobar at the surface, as has been previously stated (*see* section 75), and the veer brings it more or less into parallelism with that isobaric lie at the height of about 1,500 to 2,000 feet (approximately 500 to 650 metres). The veer is then carried on slightly beyond the isobaric lie at heights between 2,000 feet (650 metres approximately) and 8,000 feet (2,500 metres approximately). The one curious exception appears to be the case of north-easterly winds at the surface. These winds veer as do the winds in the other three quadrants, but do not quite reach the lie of the surface isobars even at heights well above 2,000 feet (650 metres).

110. *Some Abnormalities.*—In general, as has been said, the wind shows an increase in velocity from the surface up to, say, 2,000 feet. Not infrequently, however, it is found to fall off from the surface upwards, or from some point near the surface. This is exceedingly likely to happen when there is no very definite pressure gradient on the surface so that katabatic or anabatic winds are likely to prevail there (*see* section 17). Such winds have no relation to the pressure gradient, and in such cases the wind very near the surface may have a velocity which is much greater than that prevailing, say, at 500 feet and above. Quite often, too, the wind at quite a low height in such cases is found to be entirely reversed in direction from what it is actually on the surface; this, again, is to be expected from the lack of relationship between katabatic and anabatic winds and the pressure distribution.

It is interesting to notice, too, that when the wind at the surface is easterly, there is often a tendency for the wind velocity to decrease with height above it. Such easterly currents, too, are often of comparatively little thickness, so that it is quite common to find great changes of direction at no great height above them.

Moreover, it needs to be emphasised that to any general statement made about wind behaviour at heights above the surface numerous exceptions exist.

111. *Wind between* 8,000 *and* 25,000 *feet.*—The first point to be stressed under this heading is that very little help need be anticipated from the pressure distribution at the surface as a means of predicting what the wind direction or force at 8,000 feet (approximately 2,500 metres) or over is likely to be.

It needs to be remembered, too, in what follows, that owing to the fact that actual experimental observations, by following small balloons from the ground or by watching shell-bursts similarly, are only possible in the absence of much low cloud, that the results obtained for this particular layer are those for practically clear sky weather.

Captain Cave* has divided his observations of winds up to 25,000 feet into five groups:—

(*a*) Those which show "solid currents"; that is, those on which, after the gradient velocity has been reached,

there is little change either in direction or velocity up to approximately 25,000 feet (7,500 metres approx.).

(*b*) Those which show a continued increase in velocity after the gradient velocity has been reached, which continued increase is unaccompanied by much change in direction.

(*c*) Those which show a decrease of velocity after the gradient velocity has been reached.

(*d*) Those which show great changes, or even reversals, in direction in the layer under consideration.

(*e*) Those which show an upper wind (either in the north-west or south-west quadrant) crossing the lower wind and probably blowing out from a distinct low pressure centre.

The following comments upon the various groups are also largely taken from Captain Cave's book.

So far as the British Isles are concerned, it appears that group *b* is the commonest form of wind distribution. Most of the increase in velocity however occurs in the lower part of the range.

Group *c*, comprising those winds which show a velocity falling off with height, seems almost entirely restricted to easterly winds and is not manifested frequently.

The big directional changes, which are the characteristic feature of group *d*, seem nearly always to be preceded by the dropping of the wind to very low velocity at the particular heights where the changes are to occur. They are due to the superposition of two currents of air of great difference in direction upon one another under conditions which are not made evident by the current synoptic charts of the surface.

Groups *d* and *e* are closely connected with the production of thunderstorms; and a sounding of the upper air which reveals either a great change of direction in the upper layers (group *d*), or an upper wind in the north-west or south-west quadrant crossing a lower wind (group *e*), may be taken as indicating a great risk of a thunderstorm occurring in some part of the neighbourhood of the place of sounding.

Much further investigational work is needed, however, and also the perfecting of some experimental means of measuring wind direction and velocity above low cloud, before really definite statements concerning the wind behaviour between 8,000 and 25,000 feet can be made.

112. *Winds above* 25,000 *feet.*—Winds above 25,000 feet (roughly 7,500 metres) are mainly in what is termed "the stratosphere," and will be treated in the chapter which deals with that part of the atmosphere.

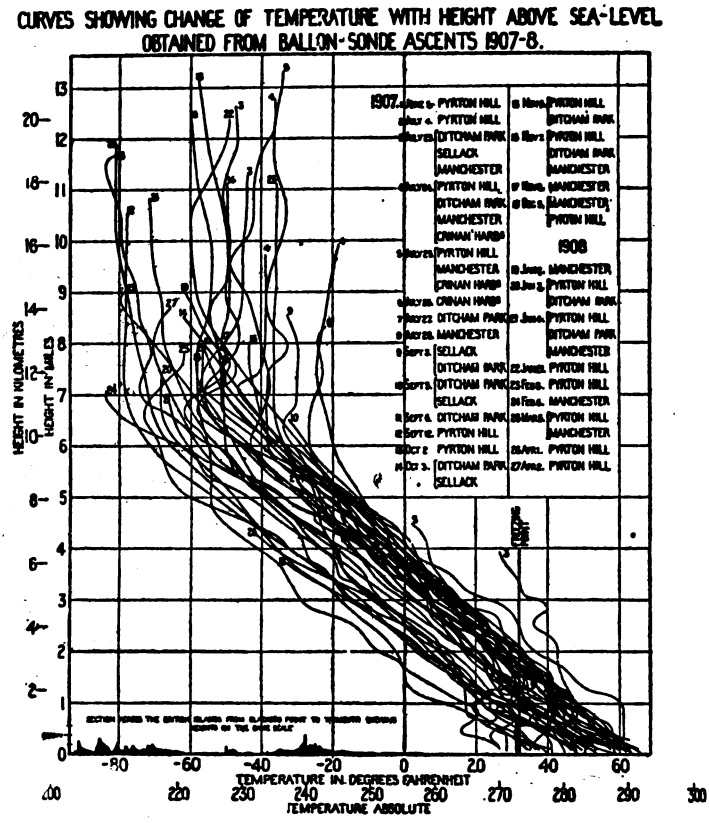
* "The Structure of the Atmosphere in Clear Weather," by C. J. P. Cave. Cambridge University Press. 1912.

CHAPTER XIX.

The Troposphere and Stratosphere.

113. *Temperature Measurements in the Upper Air.*—Measurements of temperatures in the upper air are obtained chiefly by the use of either balloons or kites.*

The data obtained reveals when plotted a most remarkable result. This result will become evident upon reference to Fig. 17, which shows the temperatures obtained in 45 soundings done for the Meteorological Office, London, in 1907–1908.


CURVES SHOWING CHANGE OF TEMPERATURE WITH HEIGHT ABOVE SEA-LEVEL OBTAINED FROM BALLON-SONDE ASCENTS 1907-8.
1907.
1908
HEIGHT IN KILOMETRES
HEIGHT IN MILES
TEMPERATURE IN DEGREES FAHRENHEIT
TEMPERATURE ABSOLUTE

The separate curves represent the relation between temperature and height in miles or kilometres in the atmosphere. The numbers marking the separate curves indicate the date of ascent at the various stations as shown in the tabular columns. The difference of height at which the isothermal layer is reached, and the difference of its temperature for different days or for different localities, is also shown on the diagram by the courses of the lines.

FIG. 17.

* For details of the methods employed, the reader is referred to the Meteorological Office, London, Publication No. 202: "The Free Atmosphere in the Region of the British Isles," which contains a Report by W. H. Dines, F.R.S., "On Apparatus and Methods in Use at Pyrton Hill."

The diagram shows that all the soundings manifest a decrease of temperature with elevation up to a height of somewhere near to 30,000 feet (approximately 10 kilometres), but that after that the temperature ceases to fall.

Considering any one ascent, it is found that the change from the region of falling temperature to that of steady, or hardly changing, temperature is generally fairly abrupt. The place of change is, indeed, often marked by an inversion of temperature, that is, by an increase of temperature with height, which inversion, however, does not persist through any great thickness of atmosphere, and soon the steady or hardly changing state is reached.

A further examination of Fig. 17 will show that the height at which the change occurs varies.

It is clear, then, that the atmosphere may be regarded as divided into two definite parts so far as temperature is concerned :—

(*a*) a lower portion in which there is a fairly regular and considerable lapse, or fall, of temperature with height; and

(*b*) an outer shell in which there is no material change of temperature with height.

The lower portion, that in which the fall of temperature with height does occur, is called the "troposphere," and the outer portion, that in which no material change of temperature occurs with height, is called the "stratosphere." Both these terms are suggested by Teisserenc de Bort. The level of change from the troposphere to the stratosphere is termed the "tropopause."

114. *The Height of the Tropopause.*—As a general rule, the boundary between the troposphere and the stratosphere is quite definite, but, in some cases, the temperature gradient ceases gradually, and, in others, it stops for some distance and then starts again. Also, inversions of temperature in the neighbourhood of the boundary are, as has already been mentioned, quite frequent.

Some definition of what, in these varying cases, is to be taken as the level of the tropopause is clearly called for; and the following are the instructions issued on the point by the Meteorological Office, London.

Type 1. When the stratosphere commence with an inversion, the level of the tropopause is the height of the first point of zero temperature gradient.

Type 2. When the stratosphere begins with an abrupt transition to a temperature gradient below 2° Absolute per kilometre (that is, 3·6° Fahrenheit per 3,280·8 feet) without inversion, the level of the tropopause is the height of the abrupt transition.

Type 3. When there is no such abrupt change of temperature gradient, the level of the tropopaus is to be

taken at the point where the mean fall of temperature for the kilometre next above is 2° Absolute or less (that is, for the 3,280·8 feet next above is 3·6° Fahrenheit or less), provided that it does not exceed 2° Absolute (3·6° Fahrenheit) for any subsequent kilometre.

The height of the tropopause varies at the same place at different times. The mean height of the tropopause at various places is given in Table VII.

TABLE VII.*

Mean Height of the Tropopause.

Place.	Period of Observation.	Number of Observations.	Mean Height of Tropopause.	
			Kilometres.	Feet (to nearest 100).
Scotland	1908–1914	29	9·8	32,200
Ireland	1908–1914	27	10·1	33,100
Manchester	1908–1914	73	10·3	33,800
England, S.E.	1908–1914	167	10·7	35,100
British Isles	1908–1910	150	11·1	36,400
" "	1912	52	10·0	32,800
Berlin, Strassburg, Vienna	1904–1909	212	10·5	34,400
Petrograd	1904–1909	41	9·6	31,500
Paris	1904–1909	90	10·5	34,400
Italy	1904–1909	46	11·0	36,100
Paris, Hamburg, Brussels	1904–1909	158	10·6	34,800

A glance at Table VII. suggests that the height of the tropopause is dependent to some extent upon latitude; and this is the case, it being lowest near the poles. The boundary level between the stratosphere and the troposphere seems, in fact, to slope downward from the equator towards the poles. This suggestion has received strong support from some ascents carried out on Lake Victoria in the equatorial regions of Africa in which the stratosphere was not encountered until a height of 55,800 feet (approximately 17 kilometres) was reached, which is about 16,000 feet (approximately 5 kilometres) above the usual maximum height in Europe.

The level of the tropopause over Enrope, too, varies with cyclonic and anti-cyclonic conditions on the surface, being lower with cyclonic conditions than with anti-cyclonic.

This suggests that there might be a definite connection between the level of the tropopause and the barometric pressure

* Geophysical Memoirs, No. 13. "The Characteristics of the Free Atmosphere." By W. H. Dines, F.R.S. Meteorological Office, London, 1919. The table has been re-arranged, part omitted, and heights expressed in feet as well as in kilometres.

at the ground level. This is, in fact, found to be the case, the mean level being lowest with the lowest pressures, and rising with increasing pressures.

115. *The Stratosphere.*—Care needs to be exercised in thinking about the distribution of temperature in the stratosphere, a care which is rendered all the more necessary because of the rather unfortunate name of "isothermal layer," which was formerly given to that outer portion of the stratosphere. The stratosphere *is* practically isothermal in the vertical direction, but it is not isothermal in the horizontal one. That is to say, if an observer with a thermometer, starting at the base of the stratosphere, could ascend straight upwards, he would find practically no change in the readings afforded by his thermometer at various stages of his ascent, but if he moved horizontally through the stratosphere, either at the level of the tropopause or along some level higher up, he would find definite and appreciable changes recorded. It is clear, therefore, that the name "isothermal layer" for the stratosphere is very unsatisfactory as liable to lead to wrong ideas; and it has now been superseded, the term "stratosphere" having come into general use.

116. *Temperature in the Troposphere.*—As would be expected from what has been already said about the variation of insolation received under different conditions by the earth's surface, and by the further differentiation effected by the two components of that surface, land and water (*see* section 14), the temperature of the air in the 2,000 or 3,000 feet (650 or 900 metres approximately) just above the earth's surface is subject to considerable fluctuations. It has been stated, too, that inversions of temperature near the ground (*see* section 23) are quite common.

Despite these fluctuations, however, it is valuable to examine the mean temperature at various heights. Table VIII. is that given by Mr. W. H. Dines, F.R.S.*; it shows the mean monthly temperatures for England. Mr. Dines has "smoothed" it to get rid of artificial irregularities. He gives his table in kilometres and degrees Absolute. In Table IX. his data has been transferred to read in feet and degrees Fahrenheit to meet the situations concerning units set out in section 104.

117. *The Seasonal Variation of Temperature in the Troposphere.*—It is interesting to inquire as to how far upward the seasonal variation of temperature, which is so marked a feature of the ground level, extends. An examination of the data given in either Table VIII. or IX. for England, and also of similar tables which have been prepared for other localities, reveals the fact that the seasonal variation extends upwards for about 30,000 feet (roughly 10 kilometres), after which there is little change.

* Geophysical Memoirs, No. 13. "The Characteristics of the Free Atmosphere." W. H. Dines, F.R.S. Meteorological Office, London (M.O. 220c), 1919.

Table VIII.

Mean Monthly Temperatures for England, smoothed.

Height in Kilometres.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
	200° Absolute +.											
14	16	17	19	21	22	23	22	21	19	17	16	15
13	16	17	19	21	22	23	23	21	19	18	17	16
12	17	18	19	20	21	22	22	21	20	19	18	17
11	17	17	17	19	20	21	22	22	21	20	19	18
10	20	20	20	22	24	25	26	26	26	24	23	21
9	24	23	24	26	29	32	34	33	33	31	28	25
8	30	29	30	32	36	38	41	41	41	38	35	32
7	37	26	37	39	42	45	47	48	47	45	41	38
6	43	43	44	46	49	52	55	55	54	51	49	45
5	50	49	50	52	56	59	61	62	61	58	55	52
4	57	56	57	59	62	65	67	68	67	64	61	58
3	63	62	63	65	68	71	73	74	73	70	67	64
2	67	66	67	70	73	76	78	79	78	75	72	69
1	71	71	73	76	79	82	83	83	81	79	75	72
0	76	76	77	82	85	88	89	89	86	83	80	77

TABLE IX.

Mean Monthly Temperatures for England, smoothed.

(Expressed in degrees Fahrenheit with heights in feet.)

Height in feet (nearest 100).	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
	Fahrenheit (nearest degree).											
45,900	−71	−69	−65	−62	−60	−58	−60	−62	−65	−69	−71	−72
42,700	−71	−69	−65	−62	−60	−58	−58	−62	−65	−67	−69	−71
39,400	−69	−67	−65	−63	−62	−60	−60	−62	−63	−65	−67	−69
36,100	−69	−69	−69	−65	−63	−60	−60	−60	−62	−63	−65	−67
32,800	−63	−63	−63	−60	−56	−53	−53	−53	−53	−56	−58	−62
29,500	−56	−58	−56	−53	−47	−42	−38	−40	−40	−44	−49	−54
26,200	−45	−47	−45	−42	−35	−31	−26	−26	−26	−31	−36	−42
23,000	−33	−35	−33	−29	−24	−18	−15	−13	−15	−18	−26	−31
19,700	−22	−22	−20	−17	−11	− 6	0	0	− 2	− 8	−11	−18
16,400	− 9	−11	− 9	− 6	1	7	10	12	10	5	0	− 6
13,100	3	1	3	7	12	18	21	23	21	16	10	5
9,800	14	12	14	18	23	28	32	34	32	27	21	16
6,600	21	19	21	27	32	37	41	43	41	36	30	25
3,300	28	28	32	37	43	48	50	50	46	43	36	30
0	37	37	39	48	54	59	61	61	55	50	45	39

118. *The Daily Temperature Range in the Troposphere.*—A similar inquiry may be put with regard to the diurnal variation of temperature, which is again so marked a meteorological feature of the ground level. Whilst it is certain that this diurnal variation decreases very rapidly with height and becomes very small, being, indeed, less than 2° Fahrenheit at 4,000 feet (that is, less than 1·2° Centigrade at about 1¼ kilometres), it seems impossible to say at what height, if any, it ceases to exist at all.

It depends to some extent upon locality. Lieut.-Col. Gold,* for example, working up results obtained at Berlin gives a daily variation there at 1 kilometre (approximately 3,280 feet) of 0·85° Centrigade (1·53° Fahrenheit) with the maximum occurring at 6 p.m., and a daily variation at 2 kilometres (approximately 6,560 feet) of 0·61° Centigrade (1·15° Fahrenheit) with the maximum occurring at noon ; whilst for Petrograd he gives the daily variation at 1 kilometre as 0·72 Centigrade (1·30 Fahrenheit), the maximum occurring at about 2.30 p.m.

119. *Yearly Mean Temperatures for Different Heights in Various Areas.*—A point of great interest is seen when the mean temperatures for different heights in certain selected areas are examined. Table X, showing some of these mean temperatures, is extracted from one given by Mr. W. H. Dines, F.R.S.†

The remarkable feature revealed by the table is the extraordinarily low temperature prevailing in the stratosphere over the equator.

120. *Temperatures over Depressions and Anti-Cyclones.*—Equally interesting results are revealed by the observations that have been taken in the upper air over depressions and anti-cyclones on the surface. Once again, we are indebted to Mr. W. H. Dines for the statistics that illustrate the matter. His figures appear in Table XI. which has been extracted with some re-arrangement and addition from one given in "The Computer's Handbook" (section II.), issued by the Meteorological Office, London. The depression figures are those connected with low pressures on the surface, the mean of the pressures being 984 millibars (29·06 inches), and the anti-cyclonic figures those connected with high pressures on the surface, the mean of those pressures being 1,031 millibars (30·45 inches). It will be noticed, too, that the mean pressures, as well as the mean temperatures, are given for the various heights.

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* Geophysical Memoirs, No. 5. "The International Kite and Balloon Ascents." E. Gold, M.A. Meteorological Office, London, Publication 210e, 1913.

† Geophysical Memoirs, No. 13. "The Characteristics of the Free Atmosphere." W. H. Dines, F.R.S., Meteorological Office, London. Publication 220c, 1919.

TABLE X.

Mean Temperatures for different Heights at different Places.

Height.		British Isles, 1908–11.		Continent (Europe), 1902-07.		Petrograd.		Equatorial.	
Kilometres.	Feet to nearest 100.	Absolute.	Fahrenheit.	Absolute.	Fahrenheit.	Absolute.	Fahrenheit.	Absolute.	Fahrenheit.
20	65,600	220	−63·4	—	—	—	—	193 ?	−112 ?
19	62,300	220	−63·4	—	—	—	—	193 ?	−112 ?
18	59,100	220	−63·4	—	—	—	—	193 ?	−112 ?
17	55,800	220	−63·4	—	—	—	—	193	−112
16	52,500	220	−63·4	—	—	—	—	195	−108·4
15	49,200	220	−63·4	—	—	—	—	198	−103
14	45,900	220	−63·4	218·6	−65·9	—	—	203	− 94
13	42,700	219·8	−63·8	218·5	−66·1	—	—	211	− 79·6
12	39,400	219·8	−63·8	218·8	−65·5	222·2	−59·4	219	− 65·2
11	36,100	219·6	−64·1	220·2	−63·0	221·7	−60·3	227	− 50·8
10	32,800	223·1	−57·8	223·4	−57·3	222·4	−59·1	235	− 36·4
9	29,500	228·9	−47·4	228·6	−47·9	224·9	−54·6	243	− 22·0
8	26,200	235·0	−36·4	235·0	−36·4	229·6	−46·1	251	− 7·6
7	23,000	241·8	−24·2	242·2	−23·4	235·9	−34·8	258	5·0
6	19,700	248·9	−11·4	249·7	− 9·7	242·6	−22·7	265	17·6
5	16,400	255·5	0·5	256·1	1·6	249·0	−11·2	272	30·2
4	13,100	261·7	11·7	262·3	12·7	255·0	− 0·4	279	42·8
3	9,800	267·7	22·5	268·0	23·0	260·9	10·2	285	53·6
2	6,600	272·6	31·3	273·1	32·2	266·2	19·8	290	62·6
1	3,300	277·0	39·2	277·6	40·3	270·9	28·2	295	71·6
0	0	282·6	49·3	280·9	46·2	276·1	37·6	300	80·6

British Isles Data. — Annual Supplement to "Geophysical Journal."

Continental Data.—"Die Temperaturverhaltnisse in der frein Atmosphäre." Wegener. 380 observations.

Petrograd Data. — "Meteorologische Zeitschrist," January 1911. Rykatchew. 90 observations.

Equatorial Data. — "Monthly Weather Review," November 1915.

Table XI.

Average Values of Pressure and Temperature at Various Heights over High-Pressure and Low-Pressure Areas.

Height.		Depressions.			Anti-Cyclones.		
Kilometres.	Feet to nearest 100.	Pressure (Millibars).	Temperature (° Absolute).	Temperature (° Fahrenheit).	Pressure (Millibars).	Temperature (° Absolute).	Temperature (° Fahrenheit).
15	49,200	116	—	—	123	—	—
14	45,900	135	224	−56	146	215	−72
13	42,700	157	226	−53	171	215	−72
12	39,400	183	225	−54	201	217	−69
11	36,100	212	225	−54	235	221	−62
10	32,800	247	225	−54	273	226	−53
9	29,500	288	226	−53	317	233	−40
8	26,200	335	227	−51	366	240	−27
7	23,000	388	232	−42	422	247	−15
6	19,700	449	240	−27	483	254	− 2
5	16,400	516	248	−13	552	261	10
4	13,100	591	255	0	628	267	21
3	9,800	675	263	14	713	272	30
2	6,600	767	269	25	807	277	39
1	3,300	870	275	36	913	279	43
0	0	984	279	43	1,031	282	48

An examination of Table XI. shows the following points:—

(*a*) That up to 10 kilometres (roughly 33,000 feet) temperatures over cyclonic areas are lower than those over anti-cyclonic ones; but that, above that level, that is, roughly from the base of the stratosphere upwards, temperatures over the low pressures are higher than those over the high.

(*b*) That even at the greatest heights examined the low pressure evident at the surface in depressions continues to manifest itself.

This latter point (*b*) seems to suggest that depressions on the surface must be deemed to extend to great heights, a matter of interest in any discussion as to the origin of cyclones and anti-cyclones. It is now thought, indeed, that pressure changes on the surface are mainly due to changes occurring in the stratosphere.

The old idea that the cores of depressions are composed of relatively warm moisture-laden air must also be discarded. Table XI. shows clearly enough that the lower layers over depressions have temperatures which are relatively low compared with the surroundings. Comparison, too, of the

temperatures over depressions reveal the fact that they are actually lower than the normals for the levels considered.

121. *Temperature Gradients in the Troposphere.*—Normally, the temperature falls off with height until the stratosphere is reached. The rate of change per kilometre step of vertical height is termed the "temperature gradient." Although normally, as has been said, the temperature falls with height, the reverse is often noticed, so that the temperature gradient may be either positive or negative. By international agreement it is deemed positive when the temperature is falling on the particular step of height examined, and negative when the temperature is rising. An inversion of temperature (*see* section 23), then, is just a change from a positive temperature gradient to a negative one. Such inversions in the various layers of the troposphere are quite common, happening almost invariably in and just above layers of fog, and frequently in and just above other forms of clouds.

The term "gradient" seems to have become somewhat overworked in the subject and it is better to restrict it to changes on the horizontal. Another term, "lapse" (Latin, *lapsus*, a slip), is coming now into use in the discussion of temperature and pressure changes in the vertical. Using the newer nomenclature, "vertical temperature gradient" becomes "lapse rate."

Measurements of this lapse rate have been fairly numerous.

Berson,* for example, dealing with data obtained from manned balloons towards the close of the last century, drew attention to the marked constancy of the lapse rate, about 5° Centigrade per kilometre (9° Fahrenheit per 3,300 feet, approximately), up to a height of 4 kilometres (roughly 13,000 feet), and to the sudden and considerable increase in its value in the next and succeeding layers. He attributed the change to the fact that the level of 4 kilometres marks roughly the upper limit of the lower clouds, and that near this height inversions of temperature are more frequent than at neighbouring heights, inasmuch as temperature inversions are characteristic of the top of such cloud layers.

Values deduced by E. Gold from later manned balloon ascents on the Continent (1901–1907) do not show the peculiarity commented upon by Berson quite so clearly, but, nevertheless, it is still distinctly noticeable. Gold's values† are given in Table XII.

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* "Wissenschaftliche Luftfehrten," Braunschweig, 1899, 3 vols.

† Geophysical Memoirs, No. 5. "The International Kite and Balloon Ascents," E. Gold, M.A. Meteorological Office, London, 1913.

TABLE XII.

Upward Temperature Gradient.

Height:—								
Kilometres -	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8
Feet (in hundreds).	0–33	33–66	66–98	98–131	131–164	164–197	197–230	230–262
Gradient:—								
Degrees Absolute.	4·3	5·1	5·1	5·8	6·2	6·9	7·5	6·2
Degrees Fahr.	7·7	9·2	9·2	10·4	11·2	12·4	13·5	11·2
Number of Cases	50	50	44	40	34	22	10	3

Similar work in determining temperature gradients or lapse rates in the upper air done in various places reveals the fact that the gradient ceases to exist at different heights in different latitudes, the higher the latitude, that is, the nearer the Pole, the lower being the height. This would be expected from what has already been said (*see* section 114) about the lowering of the level of the tropopause with higher and higher latitudes.

122. *Winds in the Stratosphere.*—Any statement concerned with winds at such a great height as is connoted by the stratosphere must be tempered by the fact that comparatively few experimental soundings have been made reaching such heights, and then only in clear sky condition, inasmuch as the small balloon method, practically the only one possible, cannot be used to high altitudes in the presence of low cloud. The results obtained, then, can hardly be used, at present, to make sound generalisations. What generally seems to happen, however, is that there is very little change of direction shown, either in the transition from the troposphere to the stratosphere, or in the actual stratosphere itself; but that velocity falls off fairly rapidly. The falling off in velocity is in agreement with the equality of pressure which is found in the stratosphere. It seems hardly possible to say much more at present about the winds in the stratosphere; better experimental methods for sounding the atmosphere at such great heights being needed, and especially some method applicable in all types of sky conditions.

CHAPTER XX.

Pressure, Density, and Humidity in the Upper Air.

123. *Variation of Pressure with Height.*—The variation of pressure with height is closely connected with the temperature of the air. The formulæ in general use is :—

$$h_1 - h_0 = C\theta\ (\log p_0 - \log p_1)$$

where h_1 and h_0 are the heights at two points vertically over each other, p_1 and p_0 the pressures at those points, θ the absolute temperature of the column of air between those points, and C is a numerical constant. If heights are measured in metres, C is 67·4 ; if in feet, 221·1.

Speaking quite strictly, the formula only holds if temperature conditions are uniform, but no great error is introduced if θ is taken as the mean temperature of the air between the two points.

But it is just the determination of what is to be taken as θ, the mean temperature, that presents difficulty in practice. As has been already shown, the temperature in the first few thousand feet is subject to great fluctuations, and no lapse rate could be assumed which would be adequate to meet all possible cases.

Obviously, the best plan would be to make actual observations of the temperature, say, at every 500 feet, on every occasion that the formula was to be used. The mean of these many readings would give a fairly accurate θ. But this is quite clearly out of the question on most occasions, and, even if it were possible and if the temperatures were taken by actual observation of a thermometer on an aeroplane, it must be remembered that the accuracy of such observations is somewhat seriously in doubt ; first, because there is a vicious circle in that aeroplane heights are measured by altimeters (*see* section 124) which depend entirely upon measurements of pressure and have to be calibrated on a temperature assumption, and, second, because the thermometers carried are, to some extent, affected by the aeroplane, and especially by the necessarily hot engine.

In view of this, the one course remaining is to adopt such a standard lapse rate of temperature which shall afford the best possible approximation to general conditions. This rate is usually taken as 6° centigrade per kilometre (that is, 3·3° Fahrenheit per 1,000 feet). Hence, if one temperature actually existent be known, the value of θ can be readily calculated.*

* Recently, Toussaint's formula for the change of temperature with height has received much recognition. The formula is—

$$T = T_0 - 6{\cdot}5\ h,$$

where h is measured in kilometres and T_0 is the temperature at the surface and T the temperature at height h, both T_0 and T being measured in degrees Centigrade.

When cases of temperature inversion at the surface are suspected, the temperature actually occurring at or near that surface would obviously be a very bad starting point.

124. *The Altimeter.*—In view of the almost universal use of the altimeter in modern aircraft as an indicator of height, some discussion of it seems pertinent.

It is an ordinary aneroid barometer (*see* section 70) graduated to show heights instead of actual pressures, and the mechanism is so devised that the height scale may be uniform. The fact that it is really an instrument for measuring upper air pressures even though it expresses them as heights justifies the inclusion of the consideration of it in this particular chapter.

It is clear that the scale of the altimeter must be graduated with regard to some definite temperature. That temperature is taken in England as 50° Fahrenheit (283° Absolute), this particular standard being due to Airy. Airy's rule for correcting the readings given by his height scale reads as follows:—When the temperature differs from 50° Fahrenheit, the recorded height is to be $\begin{matrix}\text{in}\\\text{de}\end{matrix}$creased by the $\frac{1}{1000}$th part for every $\frac{1}{2}$° $\begin{matrix}\text{above}\\\text{below}\end{matrix}$ 50° Fahrenheit. Speaking more strictly, the fraction should read $\frac{1}{1020}$ instead of $\frac{1}{1000}$. When the Absolute scale is used, the rule becomes as follows:—When the temperature differs from 283° Absolute, the recorded height is to be $\begin{matrix}\text{in}\\\text{de}\end{matrix}$creased by the $\frac{1}{283}$rd part for every degree $\begin{matrix}\text{above}\\\text{below}\end{matrix}$ 283° Absolute.

When no actual temperature observations are made on the aeroplane itself, so that the temperature at any level is not experimentally known for the purpose of correcting the height recorded by the altimeter, then a lapse rate of 1·5° Absolute (2·7° Fahrenheit) per 1,000 feet should be assumed.

The temperature correction is not, however, the only one that must be made if the height scale is to show even an approximately correct reading.

In the formula previously quoted (section 123):—

$$h_1 - h_0 = C\theta\,(\log p_0 - \log p_1),$$

if h_0 be sea level, then it may be written as zero and p_0 becomes the pressure at sea level.

Further, remembering that the formula applies to points vertically beneath one another, p_0, at any moment of observation, at any moment of reading the altimeter, is implied to be the pressure at sea level immediately underneath the observer. But the pressure at sea level differs from place to place and from time to time. The observer has set his altimeter scale at zero against the sea level pressure of his starting point. Obviously, then, if the observer retain the same zero on his

instrument throughout a long flight, his height readings will be much in error.

Meteorology can do much to help the observer in this matter. Let it be assumed that he is preparing to make a flight from London to Carlisle, and that he contemplates starting at 10 a.m. By the time of start he could be supplied with a synoptic chart showing the distribution of pressure over England at, say, 7 a.m. that same morning. Fortunately, horizontal changes of pressure are fairly persistent, and such a synoptic chart would be of service to him for some hours after it was drawn. From it, he would be able to see at a glance the pressures that prevailed at 7 a.m. along his route and, by looking at the barometric characteristics and tendencies (*see* section 73) also recorded on the chart, would be able to see, especially if provided with a forecast of coming pressure changes by a competent meteorologist, what the pressure at sea level would be likely to be at any known point of his route. During the flight, then, he could alter the zero of his altimeter to agree with the sea level pressures over which he is flying, and hence his instrument will give him a much closer approximation to his true height. The method outlined may not be perfect but it is a far superior one to that which assumes that the sea level pressure at London is the same as that at Carlisle, and that it will not alter appreciably with time.

An even better method, when it is available, is that, on passing over or near to a meteorological station, he should obtain the sea level pressure prevailing at that station directly from it by means of wireless telegraphy and then correct his altimeter accordingly.

The altimeter is, however, an unsatisfactory instrument, mechanically, for measuring pressures, and hence heights, because of the "lag" which characterises it. The "lag" becomes evident in that the mechanism will not record the proper pressure at once. Especially is this the case if it has been kept at a low pressure, that is, a great height, for an hour or so; on its return, it indicates less than the proper pressure, that is, more than the proper height, and only gradually recovers. Other mechanical defects due to the effect of the acceleration of the aeroplane upon it also arise in practice.

125. *Mean Pressures in the Upper Air.*—There is no method of measuring directly the pressure at various heights in the upper air with accuracy. Mr. W. H. Dines, F.R.S., uses the following to arrive at the pressures required. A small hydrogen-filled balloon has a meteorograph attached. A meteorograph* is a small light instrument which gives an automatic

* For a description of the meteorograph, *see* "The Computer's Handbook." M.O. 223, Section II., Subsection II. Meteorological Office. London.

record of pressure and temperature. The balloon, carrying the meteorograph, is released and its course is followed from the ground by means of two theodolites at the ends of a long base line. This means that the height of the balloon, at any given time, can be calculated trigonometrically without much likelihood of serious error. The surface pressure is read from a standard mercurial barometer. Let it be supposed that this surface pressure is x millibars. When the meteorograph is recovered (after it has fallen owing to the bursting of the balloon), its continuous record of temperature will enable the mean temperature between the recorded pressures of x and, say, y millibars to be determined. Hence the height at which the pressure was y millibars can be computed. A similar operation can be worked through using the pressure of the y millibars at the computed height as starting point; and, so continuing, the pressures at various heights can be obtained.

Table XIII. is extracted from the larger table given by Mr. Dines.* It shows the mean pressures at each kilometre height up to 20 kilometres (roughly 66,000 feet) at various places, and reveals that there is no appreciable variations in mean pressure with longitude, but that there is with latitude, the pressure being lower in higher latitudes than in lower though the Canadian values seem somewhat exceptional, perhaps owing to paucity of observations.

126. *Seasonal Variation of Pressure at Various Heights.*—Another interesting store of statistical data is given by Mr. Dines in the same publication as that from which Table XII. was extracted. Table XIV. is a copy of that given by him (with the exception that a column giving heights in feet is included) and shows the mean pressures at various heights over England for the various months of the year. The lower pressures in the winter at the higher levels should be noted. They are produced chiefly by the seasonal changes of temperature at those heights. Mr. Dines shows the range in the last column and states that, if uniform temperature above 15 kilometres (approximately 49,000 feet) had been assumed, the range at 20 kilometres (approximately 66,000 feet) would have been 5 milibars.

127. *Densities in the Upper Air*.—The density of a sample of air is the weight, or, better, the mass, of a measured volume of it. It depends upon a variety of factors; the composition, the pressure, the temperature. It increases with pressure, decreases in reversed proportion to the absolute temperature, and also decreases with increasing content of water vapour.

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* Geophysical Memoirs, No. 13. "The Characteristics of the Free Atmosphere." W. H. Dines, F.R.S. Meteorological Office, London, 1919.

TABLE XIII.

Mean Pressures in Upper Air.

Height.		Petrograd.	Scotland.	Manchester.	Berlin.	S.E. England.	Brussels.	Paris.	Vienna.	Canada.	Equator.
Kilo-metres.	Feet, nearest 100.	Millibars.									
20	65,600	55·0	55·0	55·2	54·8	54·9	54·5	56·0	55·0	—	53
19	62,300	64·0	64·2	64·6	64·0	64·1	63·7	65·6	64·4	—	63
18	59,100	74·5	74·8	75·4	74·8	75·0	74·5	76·6	75·2	—	75
17	55,800	87·0	87·3	88·0	87·4	87·5	87·2	89·6	88·0	—	90
16	52,500	101	102	103	103	102	102	105	103	—	107
15	49,200	118	118	120	120	120	120	123	121	120	128
14	45,900	138	138	140	140	140	140	143	142	142	152
13	42,700	161	161	164	164	164	164	167	165	167	178
12	39,400	187	187	192	192	192	193	195	193	195	209
11	36,100	218	219	224	225	224	226	228	226	228	244
10	32,800	255	256	261	262	261	263	266	263	266	283
9	29,500	297	299	302	305	303	305	309	306	309	327
8	26,200	346	348	352	354	352	353	357	354	358	376
7	23,000	400	402	407	408	407	408	412	409	413	430
6	19,700	461	464	468	470	469	470	473	471	475	491
5	16,400	529	532	537	538	538	538	541	539	543	558
4	13,100	606	608	613	614	615	615	617	615	618	632
3	9,800	692	694	698	699	699	699	701	700	703	713
2	6,600	787	787	793	795	795	794	796	795	798	803
1	3,300	896	894	898	900	900	899	900	900	903	903

Table XIV.

Seasonal Variation of Pressure at each Height over England.

Height.		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Range, millibars.
Kilometres.	Feet, nearest 100.	Millibars.												
15	49,200	116	116	117	119	121	123	125	125	123	122	120	117	9
14	45,900	135	135	136	138	141	144	146	146	144	143	140	137	11
13	42,700	159	158	159	161	165	168	170	170	168	167	165	160	12
12	39,400	187	186	187	189	193	196	198	199	197	195	193	188	13
11	36,100	218	218	218	221	225	229	232	232	231	228	226	220	14
10	32,800	255	254	255	258	262	267	270	271	269	266	263	257	17
9	29,500	297	296	298	302	305	310	314	314	313	309	305	300	18
8	26,200	345	345	347	350	353	359	362	363	361	357	353	349	18
7	23,000	399	399	401	405	409	414	417	418	416	413	408	403	17
6	19,700	462	462	463	467	471	476	478	479	477	473	470	466	17
5	16,400	530	530	531	535	539	543	546	547	544	541	537	533	17
4	13,100	607	607	608	611	615	619	622	623	620	617	613	610	16
3	9,800	693	693	693	697	700	704	706	707	703	700	698	696	14
2	6,600	789	788	789	792	794	798	799	799	797	794	791	790	11
1	3,300	898	897	897	898	899	902	903	903	900	899	898	898	6

The actual formula, taking account of these various factors, which allows of the density being calculated is as follows :—

$$d = d_0 \frac{p - \frac{3}{8}e}{p_0} \times \frac{T_0}{T}$$

where d is the density to be found, and d_0 is the density of perfectly dry air under the conditions p_0 = 1,000 millibars (29·53 inches) and T_0=290° Absolute. These conditions give d_0 = 1,201 grammes per cubic meter. p is the barometic pressure in millibars of the sample of air under consideration, and e is the pressure of water vapour in the sample.

Neglecting water vapour altogether, the formula takes the simpler form—

$$d = d_0 \frac{p}{p_0} \times \frac{T_0}{T}$$

and the error introduced is quite small.

TABLE XV.

Mean Densities for Different Heights, South-East England.

Height.		Temperature.	Pressure.	Density.
Kilometres.	Feet, nearest 100.	Degrees Absolute.	Millibars.	Grammes per Cubic Metre.
20	65,600	219	55	87
19	62,300	219	64	102
18	59,100	219	75	119
17	55,800	219	88	139
16	52,500	219	102	162
15	49,200	219	120	191
14	45,900	219	140	223
13	42,700	219	164	261
12	39,400	219	192	305
11	36,100	220	224	355
10	32,800	222	261	409
9	29,500	228	303	463
8	26,200	234	352	524
7	23,000	241	407	589
6	19,700	248	469	658
5	16,400	255	538	735
4	13,100	262	615	819
3	9,800	268	699	909
2	6,600	273	795	1,014
1	3,300	278	900	1,128
0	0	282	1,014	1,253

Table XV., again extracted from a larger one given by Mr. W. H. Dines,* gives some idea of the value obtained. The

* Geophysical Memoirs, No. 13. "The Characteristics of the Free Atmosphere." W. H. Dines, F.R.S. Meteorological Office, London, 1919.

values given take no account of water vapour and this makes them a little too high as a reference to the first of the two formulas just given will make clear. The error, as has been already said, is, however, quite small even in the lower layers, where it is greatest: in the higher layers, it is almost negligible. The variation of gravity with height has also been neglected, but, once again, the error introduced by so doing is very small.

It should be noticed that the density increases with elevation. This is due to the fact that the diminution of pressure and the decrease of density due to that diminution has a greater effect than the decrease of temperature and the increase of density due to that cause.

These questions of pressure temperature, and density of various levels in the atmosphere have a very great importance in the problems of buoyancy arising in connection with balloons or airships.*

128. *Humidity in the Upper Air.*—As would be expected, relative humidity shows, in general, an increase with height up to the levels of the lower cloud layers, that is, up to the height of 1 to 2 kilometres (3,300 to 6,600 feet approximately), but after that it falls off fairly rapidly and at great heights seems always to be very low. An inversion of temperature in the upper atmosphere is nearly always characterised by a low relative humidity, this again being in accord with what would be expected.

129. *The Height of the Atmosphere.*—Very few soundings of the upper air to a greater height than 20 kilometres (roughly 12½ miles) have been made, but it is quite certain that the atmosphere extends much above that height. Formerly, the height of the atmosphere was given as about 80 kilometres (roughly 50 miles), that being the height at which the air would have no appreciable pressure. This figure, however, has had to be considerably amended as a result of the observations made on meteors. Meteors, or "shooting stars" are small solid bodies, entering the earth's atmosphere from outer space. Their velocity is so great that they generate enough heat, either by actual friction or by the compression of the air in front of them, to render themselves luminous. If various observers note the apparent position of the same meteor with regard to the stars, data is afforded whereby the angular altitude of each observer's line of sight may be determined. The intersection of these different lines of sight enables the height of the luminous streak due to the incandescent meteor to be computed. From the results so obtained, it is thought that the atmosphere extends with sufficient density to produce the phenomena of

* For a treatment of this subject the student is referred to the article of "Buoyancy" in "The Meteorological Glossary," issued by the Meteorological Office, London.

luminosity in meteors to a height of about 300 kilometres (roughly 188 miles). How far beyond this level traces of the atmosphere extend is, at the moment, purely a matter of speculation.

It is clear that much, very much, still remains to be done in the investigation of the upper air. Point has been added quite recently to this remark by the publication of an important paper by Professor S. Chapman and Mr. E. A. Milne.* Formerly, it was thought that the highest layers of the atmosphere were almost entirely composed of hydrogen. Chapman and Milne doubt the presence of hydrogen in the atmosphere and show that if hydrogen be neglected, the higher layers, say above 130 kilometres (roughly 80 miles), are composed mainly of helium, and that the very highest layers are composed practically entirely of that gas, a speculation of great interest in regard to theories concerning magnetic storms, the aurora borealis, and the like.

As was stated in section 1, however, that part of the atmosphere with which the meteorologist is concerned in his daily work does not differ appreciably in chemical composition from the actual surface layers, and, in any case, chemical composition is not, at present, of great importance to him. Nevertheless, it is of interest and may become of more vital importance to him as knowledge advances.

The change of view so recently brought about does, however, emphasise the fact that meteorology, like all live sciences, is dynamic and not static, and that its bounding edge is continually advancing.

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* The Composition, Ionisation, and Viscosity of the Atmosphere at great Heights." S. Chapman, F.R.S., and E. A. Milne. Quarterly Journal, Royal Meteorological Society, Vol. XLVI. 1920.

APPENDIX.

Further Reading.

For information concerning the conduct of a meteorological station, and for details of the various instruments employed, together with tables necessary for the proper working up of the readings afforded by the instruments, the student is referred to "The Observer's Handbook," issued by the Meteorological Office, London.

For questions more particularly relating to physical geography, "The Realm of Nature," by Dr. H. R. Mill (Murray), still remains one of the best written in English, containing a fund of information in a comparatively small compass.

Of text-books on general meteorology, R. G. K. Lempfert's "Meteorology" (Methuen & Co.), A. E. M. Geddes' "Meteorology" (Blackie), and W. J Humphreys' "Physics of the Air" (Philadelphia, Franklin Institute), may be thoroughly recommended.

A. W. Clayden's "Cloud Studies" (John Murray, London), and G. A. Clarke's "Clouds" (Constable & Co.) are also strongly to be recommended on their particular subject.

For definitions of terms employed and for short but authoritative articles upon various aspects of the subject, arranged alphabetically, "The Meteorological Glossary," issued by the Meteorological Office, London, should be in the hands of all earnest students of the subject. It is, at once, very comprehensive, very clear, and very cheap, and its information is thoroughly to be trusted.

For fuller discussions of the problems arising in connection with forecasting weather from synoptic charts, Sir Napier Shaw's "Forecasting Weather" (Constable & Co., London) will repay the most careful study. It is extremely valuable in that it forces attention to the intimate relationship existing between physics and meteorology. From the historical point of view, "Weather," by the Hon. R. Abercromby, the writer and worker who did so much to crystallise knowledge concerning forecasting from synoptic charts, is full of interest and still remains full of instruction.

For certain broad aspects of meteorology in relation to man, Dr. H. N. Dickson's "Climate and Weather" (Home University Series, Williams and Norgate, London), is very valuable.

For fuller reading on the conditions prevailing in the upper air, the student is referred to the "Manual of Meteorology" (Part IV.), by Sir Napier Shaw, F.R.S., which has, as its sub-title, "The Relation of the Wind to the Distribution of Barometric Pressure," and which is published by the Cambridge University Press; and to C. J. P. Cave's "The Structure of the Atmosphere in Clear Weather," published by the same press. Reference should also be made to "The Characteristics of the Free Atmosphere," by W. H. Dines, F.R.S., which is issued as Geophysical Memoirs, No. 13, by the Meteorological Office, London, and to "The International Kite and Balloon Ascents" (Geophysical Memoirs, No. 5), by E. Gold, F.R.S., issued by the same office. Both these last-mentioned are standard works upon the subject of which they treat.

Meteorology is, however, a distinctively live science, and new and important work is being done in it daily in various countries and published in various forms and languages. So far as the United Kingdom is concerned, most new work is to be found in the current publications of the Royal Society of the Meteorological Office, London (especially in the two series known respectively as "Geophysical Memoirs" and as "Professional Notes"), and of the Royal Meteorological Society (Quarterly Journal).

If the student wishes to maintain himself abreast of new knowledge and of new view points in the subject, a periodical inspection of these publications is essential.

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